Morphology of the Avon-Heathcote Estuary Mouth

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Abstract

This thesis concerns the morphology of the Avon-Heathcote estuary mouth, located near Christchurch, New Zealand. While there have been numerous studies of tidal inlet morphology in the United States, there have been comparatively few on the inlets around the New Zealand coast.

Morphology was found to vary considerably during the study with substantial changes in both the beach systems and the ebb tidal delta. These changes occurred despite the absence of any major storm events and beach changes were related to the onshore migration of the delta marginal channels.

The transport of sediment in the vicinity of the estuary mouth was found to be in a predominantly southward direction. Direct exchanges between the updrift and downdrift beaches however, where prevented by the presence of the main ebb channel. Sediment therefore was transported into the estuary on the flood tide and then out again on the ebb tide in a manner consistent with a tidal bypassing regime.

The change in the beach system around the spit of South Brighton spit was of a high magnitude although the pattern of erosion at South Brighton and subsequent deposition in Clifton Bay appears to be part of a larger cycle regularly occurring in this environment.

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Chapter One: Introduction

1.1 Introduction

The mouths of estuaries are amongst the more complex of all coastal environments. They represent the interface between marine, terrestrial, and fluvial processes and it is this aspect of estuary mouths which sets them apart from most other coastal environments. The interaction of these three sets of processes create a number of interesting and unique coastal phenomena, such as spits and ebb and flood tidal deltas.

Estuaries and their mouths have historically, and remain, important coastal resources. They are used extensively for navigation and recreation (Bruun, 1966) and in addition to this housing and amenities are increasingly being located in zones influenced by the highly variable processes which occur in the vicinity of estuary mouths. Sediment is frequently dredged from many of the worlds' inlets, either to keep the inlet channel clear for navigation or for use as aggregate for industry (Hicks and Hume, 1993). Despite this however, there is a lack of knowledge regarding the response of tidal inlets to dredging and other naturally occurring processes, including long term processes such as sea level rise (Aubrey and Weishar, 1988).

There has been an increase in tidal inlet research during the past four decades reflecting their importance as coastal resources. However, much of the research into the morphology of estuary mouths and tidal inlets has been carried out on the east coast of the United States (e.g. Hayes, 1975; Hubbard, Oertel and Nummedal, 1979; Smith and FitzGerald, 1994) and on the Dutch coast (e.g. Bruun and Gerritson, 1960; Bruun, 1978). The bulk of research into inlet morphology then, relates to environments where there are 'broad coastal plains with well developed drainage basins and extensive barrier islands with numerous tidal inlets' (Hicks and Hume, 1993).

There have however, been comparatively few investigations into inlet morphology in tectonically active environments, such as New Zealand. New Zealand estuaries and inlets are distinct from those found on the United States east coast in that they are located on 'narrow coastal plains with generally small, high relief drainage basins, and are nearly always associated with bedrock headlands' (Hicks and Hume, 1993).

In addition to this, most studies have tended to focus on long term, broad changes in inlet morphology and surrounding coastline (e.g. Pringle, 1983; Findlay and Kirk, 1988). In comparison, there has been a general lack of research that quantifies short term changes in delta and associated beach systems. In particular, the nature and processes involved in the exchange of sediment between the two systems has received relatively little attention in the literature until recently (e.g. Oertel, 1988; FitzGerald, 1988; Smith and FitzGerald, 1994).

This thesis therefore, attempts to redress dearth of knowledge on short term variations in tidal inlet morphology. In particular, it is concerned with the short term variations in morphology at the mouth of the Avon-Heathcote estuary, located near Christchurch, New Zealand. More specifically, it is concerned with the interactions between the inlet channel, and the delta and beach systems and patterns of sediment transport that arise from these interactions. The broad aims of this thesis then were:

1) To describe and quantify short term changes in the morphology of the estuary mouth.

2) To account for these changes with regard to the processes active in this environment and elucidate the resulting patterns of sediment transport.

3) To compare the findings of this study with models of inlet morphology development relating to tidal inlets in other parts of the world.

1.2 The Study Site

This study relates to the mouth of the Avon-Heathcote estuary located near Christchurch, New Zealand as shown in Figure 1.1. The estuary is mesotidal, triangular in shape and has a surface area of 8 km^2, with 95 percent of this consisting of intertidal sands (Hutchinson, 1972). The estuary takes its name from the two rivers that flow into it. The Avon River flows into the northeastern corner and the Heathcote into the southwestern corner. Their combined catchments give the estuary a total catchment area of 200 km^2 (Heath, 1976).

To the south and southwest the estuary is bounded by the Port Hills which are of volcanic origin. To the northwest and north lie suburbs of Christchurch that were extensive swamplands until European settlement in the 1850s (Penney, 1982). The eastern boarder is demarked by Brighton Spit, a five kilometre sand spit, which runs in a northwest-southeast direction. The estuary has only one outlet channel which runs out to sea between the distal end of the spit and Clifton Hill in the south.

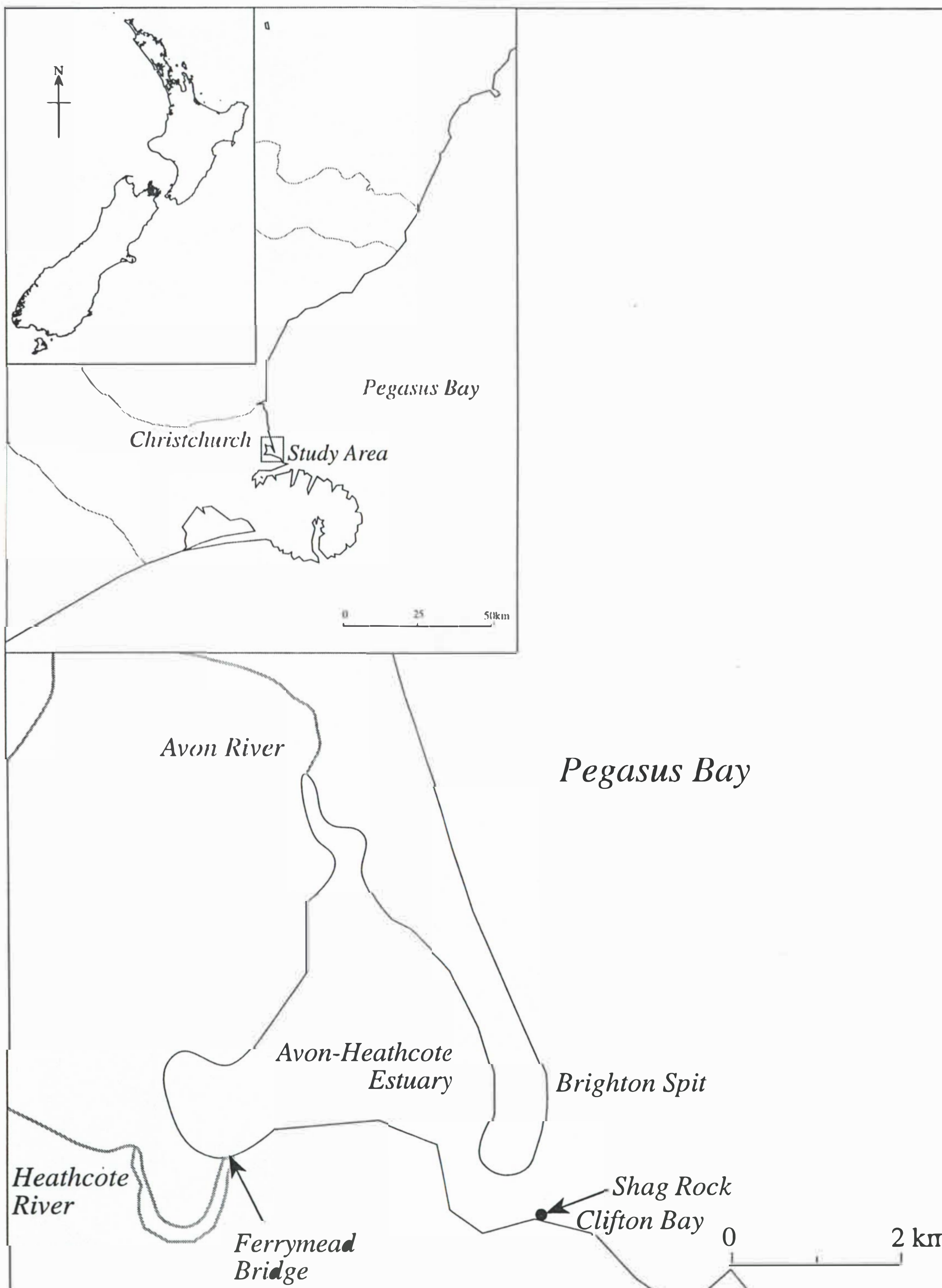


Figure 1.1 The Avon-Heatcote Estuary

1.3 Thesis Outline

The following chapter will review the literature relating to estuarine environments. In particular it is concerned with spit and delta development, tidal inlet stability, and marine and fluvial processes.

Chapter Three will summarise previous studies relating to the morphology and processes in the vicinity of the Avon-Heathcote estuary mouth.

Chapter Four will present data from 10 profile sites for the period November 1993 to August 1994 and these will be placed in the context of longer term data available at some of the sites.

Chapter Five will detail the methodology employed for remote sensing the ebb-tidal delta using time exposure photography. It will then document the broad changes that occurred in the delta system between December 1993 and August 1994.

Chapter Six will describe the processes influencing morphology at the mouth of the Avon-Heathcote estuary and will also evaluate these in light of the longer term records that exist.

Chapter Seven will assimilate the data presented in the three preceding chapters to provide a general model of sediment transport in the vicinity of the estuary mouth. The results will also be evaluated in the context of the longer term patterns discussed in Chapter Three.

Conclusions will be made in Chapter Eight. This will include a summary of the major findings and will reflect on these in terms of the established literature concerning estuary mouths.

Chapter Two: Tidal Inlet Morphology

2.1 Introduction

The morphology of tidal inlets has become the subject of serious scientific study in only the past two decades, although the study of the dynamics of inlet gorges themselves has been the subject of inquiry for longer, reflecting their importance as navigational routes (e.g. O'Brien, 1931; Bruun and Gerritson, 1960). The deltaic deposits that may form either side of the inlet gorge have tended to be neglected due to their inaccessible nature. Because deltas store vast quantities of sediment their importance as potential sources of aggregate for building has been increasingly recognised (Hicks and Hume, 1993). This has prompted numerous studies regarding the effect of mining, particularly on ebb deltas, although there are still relatively few quantitative studies regarding the formation and short term variability of ebb tidal delta systems.

This chapter will examine general models of tidal inlet morphology before focusing on the literature relating to tidal inlet stability and the dynamics of ebb tidal deltas. Flood tidal deltas will not be examined in any detail as the Avon-Heathcote estuary does not have a flood delta. This subject is therefore not particularly relevant to this study.

2.2 Tidal Inlet Morphology

While tidal inlets can vary considerably in size and character, several authors have presented models of typical geomorphic features common to this type of coastal environment (e.g. Hayes, 1975; Smith, 1984). One such model is presented in Figure 2.1, and it can be seen that the morphology of tidal inlets can be divided into four distinct parts; the barrier enclosing the estuary, the inlet gorge, and the flood and ebb tidal deltas.

The barrier enclosing the estuary can take numerous forms. Figure 2.1 depicts a double spit enclosed estuary, although an estuary may be headland, tombolo, beach, or island enclosed (Hume and Herdendorf, 1988a). A particular estuary may also be a combination of the above, as in the case of the Avon-Heathcote, which is spit enclosed to the north and beach/headland enclosed to the south. The type of barrier enclosing the barrier may have a profound effect on the resulting deltaic morphology, as will be discussed later.

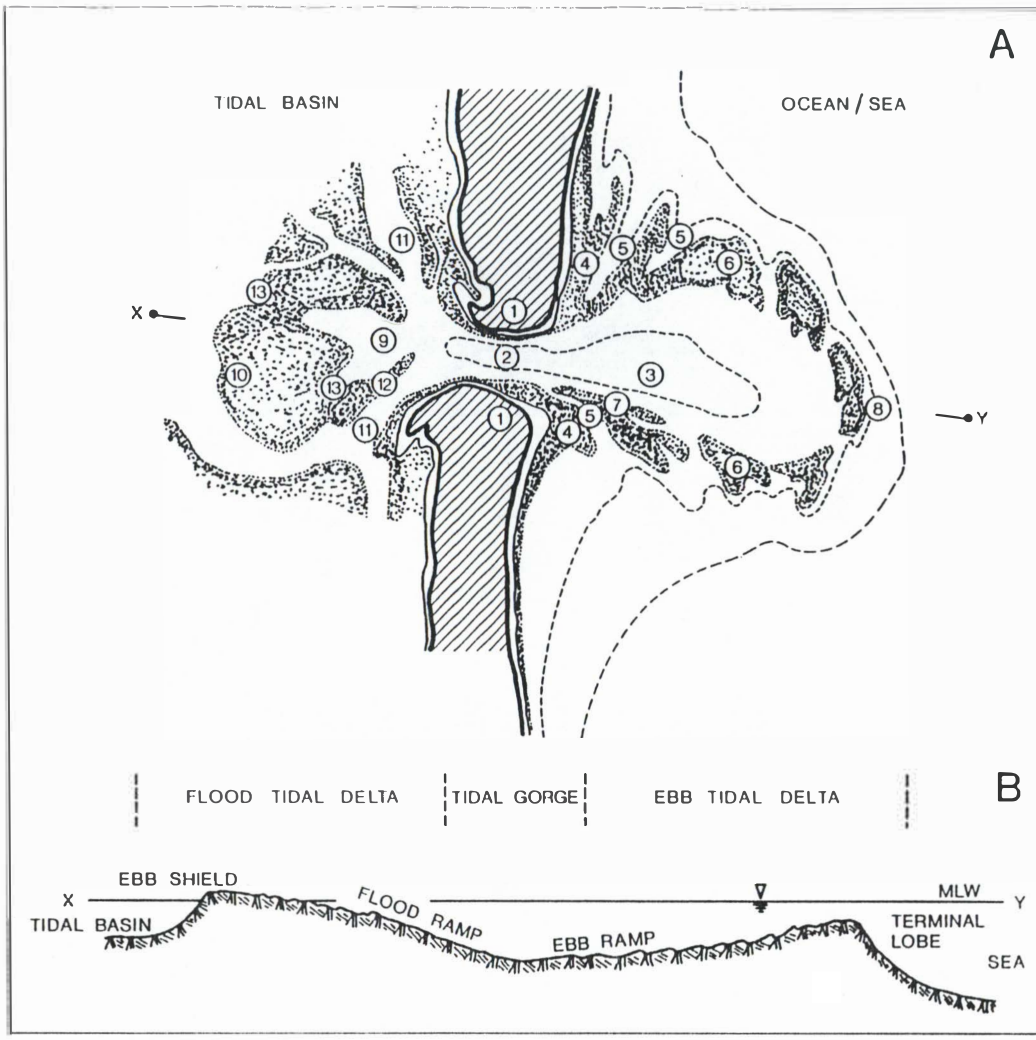


Figure 2.1a: Schematic diagram depicting the principle morphological features of a tidal inlet on a sandy coast.
1) coastal barrier or spit headland; 2) the tidal gorge; 3) the main ebb channel and ebb ramp; 4) swash platforms; 5) marginal flood channels; 6) marginal shoals; 7) ebb tidal levee; 8) ebb delta terminal lobe; 9) the flood ramp; 10) the ebb shield; 11) main ebb dominated inner channels; 12)ebb spit; 13) spill over channels
Figure 2.1b: Cross section profile from X to Y through the tidal gorge and over both flood and ebb tidal deltas.
(from Smith: 1984)

Estuary inlet gorges tend to be narrow and relatively deep due to the high velocities of the currents that flow through them on the ebb and flood tides. The exact character and dimensions of the inlet gorge are controlled by a number of factors including their geologic origin (Hume and Herdendorf, 1988b), the volume of water that passes through them on each tidal cycle (O'Brien, 1931; Heath, 1975) and the rate of sediment supply (Bruun and Gerritson, 1960; Bruun, 1978).

Flood tidal deltas are found on the landward side of many tidal inlets, although it is possible that a flood tidal delta may be absent, as is the case with the Avon-Heathcote Estuary. The principal components of a flood tidal delta are the flood ramp, flood channels, ebb shield, ebb spits and spill over lobes (Hayes, 1975; Smith, 1984). The flood ramp slopes upward from the inlet gorge and, landward of the inlet gorge, divides into a number of channels that are primarily occupied by flood tide flows. The ebb shield, represents the landward extent of sediment deposition by the flood tide, and it tends to have steep sides which serve as the channel banks of ebb tide flows. In some places the ebb shield will have marginal channels cut into it and sediment transported by the flood tidal currents will be deposited to form spill over lobes. Finally, ebb spits, as the name implies, are formed by the ebb flow and are formed at the margins of the flood delta. Ebb spits are elongate toward the inlet gorge and serve to separate ebb dominated channels from flood dominated channels. Flood tidal deltas have been demonstrated to show remarkable similarity along the eastern coast of the United States (Hayes, 1975) and also in New Zealand (e.g. Titchener, 1993).

Ebb tidal deltas lie seaward of the main inlet gorge and represent major sinks in the coastal sedimentary budget (Hicks and Hume, 1991). In many respects they are similar to flood tidal deltas although they are frequently up to ten times larger than the associated flood delta (Hicks and Hume, 1993). Typical features of ebb tidal deltas, as shown in Figure 2.1 are the main ebb channel and ebb ramp, main ebb channel linear bars (or levees), swash platforms, marginal flood channels, marginal shoals, and the ebb delta terminal lobe.

As the ebb flow passes through the inlet gorge, the flow is constricted and there is a substantial increase in current velocity (Wright and Sonu, 1975). These strong currents scour out the main ebb channel although seaward of the inlet gorge, current velocity declines rapidly allowing the deposition of entrained sediment (Smith and FitzGerald, 1994). The first of the distinctive bedforms that result from this deposition is the formation of linear bars (or levees) along the channel margin and these are a reflection of the weaker flows that occur at the channel margins.

Swash platforms are broad low relief sand shoals that form as a result nearshore wave action. Often they manifest as subaqueous continuations of the spit or headland that they form in the vicinity of, but they may also be separated from this by shallow channels (Smith, 1984). Around the margins of the ebb tidal there are usually a number of marginal shoals. These form the seaward rim of the delta and are the result of the interaction between tidal currents and wave action. As a result of this genesis they are subject to considerable variation in response to changing process conditions (Smith, 1984).

Because the ebb current continues to flow after the tide has turned (Robinson, 1960), the incoming flood tide follows a path of least resistance and scours channels either side of the main ebb channel, although later on the flood tide flows may occupy the main ebb channel (Robinson, 1960). The marginal flood channels are quite distinct from the main ebb channel and usually cut through the marginal shoals on the delta rim (Smith, 1984).

The most seaward extent of the ebb delta is referred to the terminal lobe. This tends to be a large accumulation of sediment of comparatively high relief and reflects the seaward extent of sediment transport due to tidal currents.

2.3 Tidal Inlets

O'Brien (1931) was the first to postulate that there was a simple linear relationship between the inlet gorge cross sectional area (A_c) and the volume of water that passed through it on each half tidal cycle (Ω). When plotted against each other on a logarithmic scale, cross sectional area is found to increase with increasing tidal prism, and this relationship has been found to be applicable for many tidal inlets around the world (e.g. O'Brien: 1931, 1969; Furkert, 1947; Bruun, 1991; Gao and Collins, 1994a)

This relationship was first applied to New Zealand inlets by Furkert (1947) but was later applied more extensively by Heath (1975,1976). Hume and Herdendorf (1987, 1988b) also used the relationship to evaluate the stability of a number inlets, including the Avon-Heathcote. They found that in general the inlets studied conformed to the relationship:

$A_c = 1.18 \times 10^{-3}\, \Omega^{0.846}$ (Hume and Herdendorf: 1988b) (1)

The premise implicit in this relationship is that inlets that lie close to the regression line are stable (i.e. have the ability to return to their original configuration after a disturbance (Hume and Herdendorf, 1987)). Inlets that lie above the regression line experience deposition in the inlet, while those below the regression experience erosion in the inlet. It also follows that the slope of the regression line gives equilibrium values for the mean maximum flow velocity through the inlet gorge. Bruun and Adams (1988) has found that these lie between 0.9-1.1 m/sec, when applied to numerous Dutch and North American inlets.

While this relationship is a useful initial indicator it is an oversimplification of tidal inlet stability. Bruun (1978) argues that for a more accurate assessment, littoral drift, channel width/depth ratio, sediment grain size, and bottom roughness should also be considered. Gao and Collins (1994a) applying the A_c/Ω relationship to historically stable inlets in England and China found that maximum mean current velocities in these inlets were 1.8 m/sec and 0.67 m/sec. They attributed these significant deviations from 0.9-1.1 m/sec to differences in flood and ebb tidal durations, freshwater discharges, and sediment transport through the inlet, suggesting that individual inlet characteristics can significant alter the A_c/Ω relationship.

In addition to these limitations Hume and Herdendorf (1988b) also point out that the relationship is best applied to barrier enclosed inlets that have tidal prisms in the range 10^7-10^9 m^3 and cross sectional areas in the range 10^3-10^5 m^2. Also because tidal prism and cross sectional area covary, the relationship is only a broad indicator of erosion or deposition and the relationship also does not take into account storm conditions where the variables may be very different from what they are under mean conditions.

A second relationship frequently used to assess tidal inlet stability is that which exists between the tidal prism (Ω) and the total quantity of sediment (M_{tot}) being transported to the inlet in a given year (Bruun and Gerritson, 1960; Bruun, 1978,1991; Gao and Collins 1994b). Bruun and Gerritson (1960) argue that inlet stability is given by the balance between littorally drifted sediment, which chokes the inlet, and tidal prism, which flushes this sediment out to sea, thus keeping the inlet open.

Bruun (1978) proposes critical values of Ω/M_{tot} and provides general characteristics for each range of values, as shown in Table 2.1. A particularly important feature of this relationship is that it defines the nature of the sand bypassing regime. Where the ratio between Ω/M_{tot} is in excess of 100, a tidal bypassing regime will predominate (Figure 2.2a), while for values less than 50, a bar bypassing regime will predominate (Figure 2.2b). A value between 50-100 is intermediate and the inlet will feature a combination of both tidal and bar bypassing.

Ω/M_{tot}	**Inlet Characteristics**
> 150	Conditions are relatively good, little bar and good flushing.
100-150	Conditions become less satisfactory, and offshore bar formation becomes more pronounced.
50-100	Entrance bar may be rather large, but there is usually a channel through the bar.
20-50	All inlets are typical bar bypassers. Waves break over the bar during storms, and the reason that the inlets stay alive at all is often that they, during storms they get a shot in the arm from freshwater flows. They are unreliable and dangerous for navigation
< 50	Descriptive of cases where the inlet entrance is an unstable overflow channel rather than a permanent inlet.

Table 2.1 Inlet Mouth Characteristics (after Bruun, 1978)

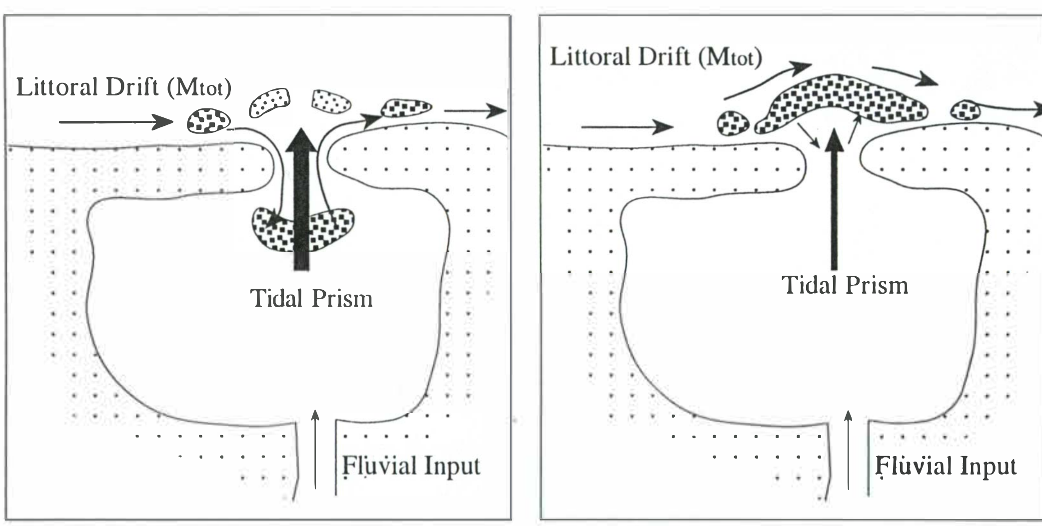


Figure 2.2a Tidal bypassing

Figure 2.2b Bar bypassing

This relationship, like the A_c/Ω one, also contains inherent weaknesses. It fails to take account of the highly variable nature of littoral drift, in terms of quantity and direction, from year to year and the difficulty in accurately calculating this variable. Both tidal prism and littoral drift may also be greatly effected by storm incidence in a given year or run of years, which would render this relationship invalid.

The relationship has also been found to represent an over simplification of tidal inlet stability. Gao and Collins (1994b), applying the Ω/M_{tot} relationship to Christchurch Harbour, southern England calculated a value of 26. With this value Bruun (1978) would argue that the inlet is 'unreliable and dangerous' and prone to blocking from the excessive deposition of sediment. The Harbour however is rarely blocked and is characteristic of those inlets that have a Ω/M_{tot} ratio of around 50 (Gao and Collins: 1994b). The relationship is greatly enhanced when tidal characteristics (Christchurch Harbour experiences a semi-diurnal tide although the tide has a 'double high' characteristic), and annual freshwater input are taken into account (Gao and Collins: 1994b).

While an indication of tidal inlet stability can be given by the ratios between A_c/Ω and Ω/M_{tot}, neither provide an entirely accurate account of stability (Bruun: 1978, Hume and Herdendorf: 1988b, Gao and Collins, 1994a, 1994b). Individual inlet characteristics are determined by a number of factors other than tidal prism, cross sectional area and littoral drift. In addition to freshwater input and tidal characteristics (Gao and Collins: 1994b), Bruun and Gerritson (1960) suggest that wave action, sediment characteristics, channel width/depth ratio, shear stress of the channel surface, and time history of the inlet are also important variables to consider when evaluating tidal inlet stability. It also follows that all of these variables may vary considerably under storm conditions and evaluation of mean conditions may give an erroneous impression of overall inlet stability.

2.4 Ebb Tidal Deltas

While it has been possible to postulate general models of ebb tidal delta geomorphology (e.g. Hayes, 1975; Smith, 1984) there is a lack of quantitative data relating to ebb delta development and behaviour, particularly under storm conditions. This lack of research is largely a result of the fact that they are often completely subaqueous sand bodies that are situated in zones of high current velocity and wave power, making their study difficult.

Individual ebb tidal deltas are a reflection of the interaction between tidal currents and wave power with the majority of deposition occurring where wave and tidal forces are roughly equal (Hubbard, Oertel and Nummedal, 1979). Wave climate is therefore is an important control on ebb tidal delta characteristics (Hubbard *et. al.*, 1979; Marino and Mehta, 1987; Oertel, 1988). This will give rise to different delta characteristics as shown in Figure 2.3. Where tidal inlets are tidally dominated, the delta will be located further offshore (Figure 2.3d), while on wave dominated coasts, the delta will be situated relatively close inshore (Figure 2.3a). The prevailing longshore current may also cause the delta to be skewed in one direction (Figure 2.3b, Figure 2.3c). It also follows, that this pattern of opposing forces, between tidal currents moving sediment offshore and wave action moving sediment onshore (Dean and Walton: 1975), may be dramatically altered during storm conditions and it would be expected that the delta would migrate inshore in response to higher wave energy.

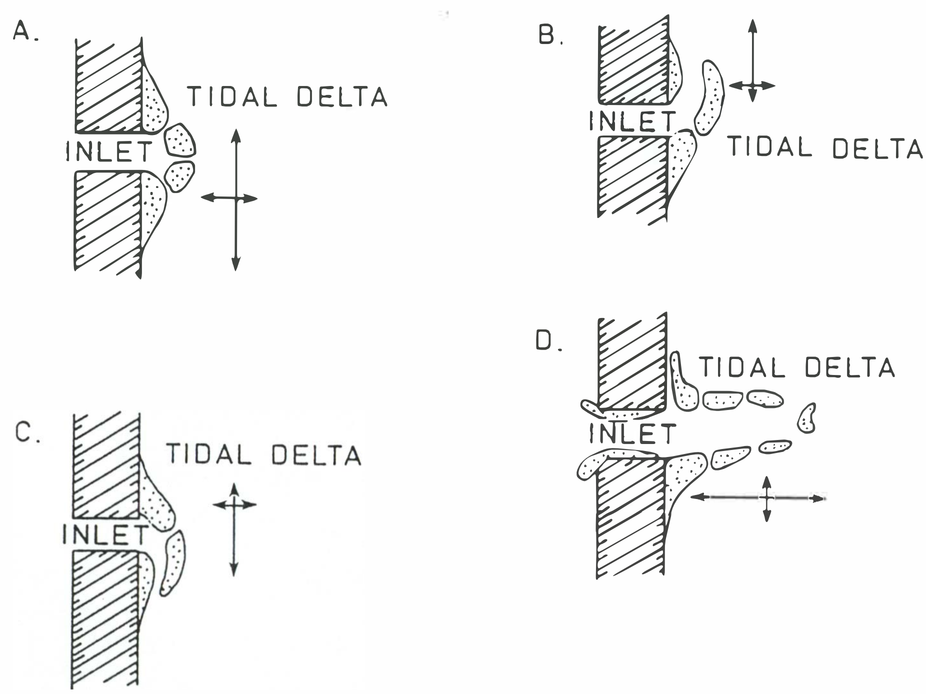


Figure 2.3 Sketch maps depicting four different types of ebb tidal deltas (from Oertel: 1988)
A. The prevailing forces of longshore and onshore currents are greater than the force of ebbing inlet currents. B. and C. The prevailing force of the southerly and northerly longshore currents, respectively, are greater than the three remaining component forces. D. The prevailing forces of the inlet currents are greater than the forces of the longshore currents.

It has also been noted by a number of authors (e.g. Robinson: 1960, Smith and FitzGerald: 1994) that longshore currents may be significantly altered in the vicinity of tidal inlets due to wave refraction around the ebb tidal delta. This can lead to a local reversal in the direction of longshore currents which in turn causes a change in deposition of sediment on beaches immediately adjacent to the inlet.

One of the most important controls on ebb delta characteristics however, is the pre-existing shoreline configuration (Sonu and van Beek, 1985; Hume and Herdendorf, 1992; Hicks and Hume, 1993). Hicks and Hume (1993) present a four way classification scheme of ebb tidal deltas found on New Zealand North Island coast, as shown in Figure 2.4. This classification focuses on the importance of shoreline configuration as a control on the area in which an ebb tidal delta can develop and the importance of ebb tidal jet alignment (Hicks and Hume, 1993).

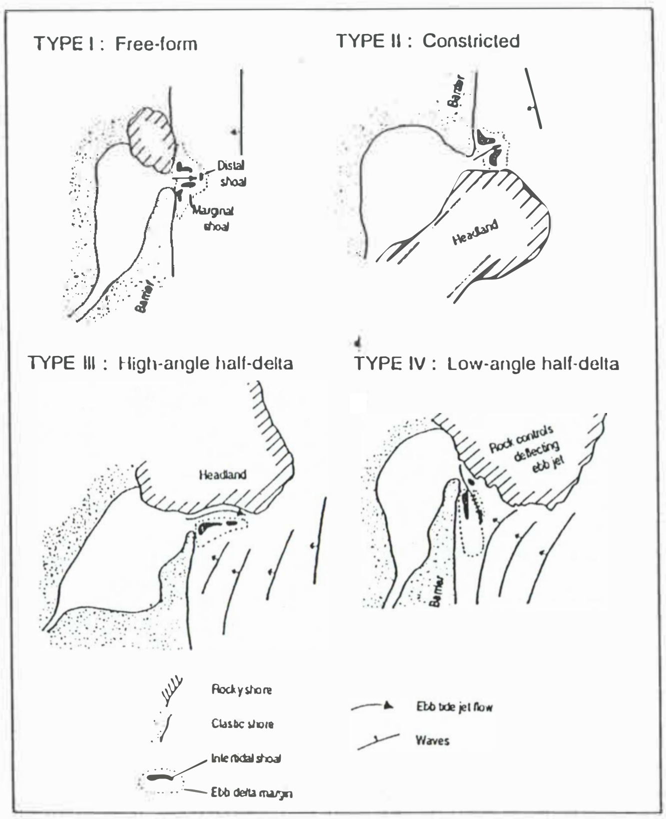


Figure 2.4 Types of ebb tidal delta found on the New Zealand coast (from Hicks and Hume: 1993)

Free form (Type I) roughly symmetrical, deltas develop on relatively straight coastlines which are moderate to high energy. A headland may or may not be present although if there is one present it does not impede the lateral growth of the delta (Hicks and Hume, 1993). Constricted deltas (Type II) are characteristic where a headland constricts the lateral development of the delta. The headland may also provide some shelter from wave action (Hicks and Hume, 1993).

Type III, a high-angle half-delta, is essentially half a delta and has an approximate 'L-shape' (Hicks and Hume, 1993). The shape is largely a result of the presence of a headland which completely impedes growth in one direction. The main ebb channel runs hard against the headland and sediment is deposited only on the beach side of the inlet. Low-angle half deltas (Type IV) are similar to high-angle half-deltas, although the low angle of the main ebb tide jet (relative to the barrier shoreline), means that the delta elongated in a longshore direction. This type of delta is often little more than a widened swash bar and can be hard to distinguish from the offshore bar system (Hicks and Hume, 1993).

Hicks and Hume (1993) also calculated a multiple regression to determine factors controlling ebb delta volume. They found that the two most important controls were spring tidal prism (Ω) and the sine of the angle of the ebb tide jet, relative to the shoreline (θ). The analysis of 16 ebb tidal deltas around the North Island of New Zealand, ranging in volume from 3.8 x 10^4 m^3 (Whitianga) to 1.23 x 10^{10} m^3 (Kaipara), gave the following relationship with a correlation of r=0.93:

$V_e = 1.37 x 10^{-3}\,\Omega^{1.32}(\sin\theta)^{1.33}$ (Hicks and Hume: 1993) (2)

Partial correlation analysis also showed that ebb tidal delta volume also increased with decreasing wave energy, decreasing inlet mean throat depth and decreasing sediment size, although these were subsidiary to spring tidal prism and the angle of the ebb tidal jet (Hicks and Hume, 1993). Hicks and Hume (1993) also point out that the time history of the ebb tidal delta can be an important variable, particularly in the case of very large tidal inlets that experience relatively low levels of littoral drift.

Similar to Hicks and Hume (1993), Hubbard *et al.* (1979) found a strong correlation between tidal range (T) and total estuary area (E) with ebb tidal delta area (A_e):

$A_e = 0.49T + 1.7E - 21$ (after Hubbard *et al.*: 1979) (3)

While delta area and tidal range are closely related to the delta volume and tidal prism parameters used by Hicks and Hume (1993), Nummedal *et al.* (1979) introduced an additional variable, that of total estuary area. The significance of this is largely ignored elsewhere but relates to the capacity of the estuary to store and supply sediment to the ebb tidal delta system.

An additional variable that has received little attention in the literature is the potential influence of fluvial derived sediment on ebb tidal delta volume. This may be considerable during high energy events with large amounts of sediment being deposited on inlet shoals in comparatively short periods of time (Hume and Herdendorf, 1987). This may also be followed by a slow onshore migration of sediment over the next 12-18 months (Hume and Herdendorf, 1987).

The possible influence of freshwater discharge on ebb delta volume is also implicit in Gao and Collins (1994b) who found that freshwater discharge may significantly alter tidal prism. It follows therefore that because there is a strong relationship between tidal prism and ebb delta volume (Hicks and Hume, 1991,1993; Hubbard *et al.*, 1979) then a relationship between freshwater discharge and ebb tidal volume would also be expected.

Several studies of eastern coast tidal deltas in the United States have investigated the nature and periodicity of change in ebb tidal deltas (Finlay, 1978; FitzGerald, 1984; Ashley, Halsey, Farrell, 1981; Smith and FitzGerald: 1994). Smith and FitzGerald (1994) found that in the short term there may be large volumes of sediment involved in transfers within the ebb delta system. They also found over a fourteen month study of Essex River ebb tidal delta, that there were significant shifts in the location of the main ebb channel and an overall onshore movement of the delta complex with substantial volumetric increases being recorded in the swash bars.

Finlay (1978) in a similar study of North Inlet, South Carolina found similar changes in ebb tidal delta volume and these were related to the seasonal variation in wave climate, with the ebb tidal delta becoming smaller in response to higher energy waves in winter.

Smith and FitzGerald (1994) found that there may also be significant variations in ebb tidal characteristics related to longer term cycles (5-7 years) and present a three stage model of delta changes for the Essex River ebb tidal delta. During Stage I, the delta is relatively small with few intertidal sand bodies. The low relief of the delta means that it does not induce wave breaking so the beach is prone to erosion by storm waves.

During Stage II, the swash bars that form near the delta terminal lobe, migrate onshore and often weld themselves to the linear channel margin bars. The large bar complexes that result dissipate wave energy over the delta and reduce energy incident on the beach. As the swash bars continue to migrate onshore, the flood channels become increasingly constricted and this leads to an increase in both wave and tidal current velocity. This subsequently leads to greater erosion of the beach.

In the final stage, the swash bars weld to the beach and the width of the foreshore is substantially increased. The lack of sediment in the ebb tidal delta however, leads to an increase in wave energy incident on the beachface and a period of erosion ensues. Eroded sediment is transported to the inlet throat and deposited on the beach downdrift of the inlet (Smith and FitzGerald: 1994). Smith and

FitzGerald (1994) offer no explanation as to the driving force of this 5-7 year cycle although their findings are similar to those of Smith (1984) at Price Inlet, also in South Carolina. This suggests that the cycle may be meteorologically driven and/or related to mid-term variations in the wave climate.

As yet there have been few studies of this nature applied to New Zealand ebb tidal deltas. Pickrill (1985) however found that between 1958-1979, the ebb tidal delta associated with Rangaunu Harbour, Northland, increased its volume by 8.53 x 10^6 m^3. While this represents annual deposition in excess of 400 000 m^3, it is not known to what extent the changes represented long term changes in the delta system or whether they were part of shorter term cyclical variations (Pickrill: 1985). Similarly the Avon-Heathcote ebb tidal delta was found to change substantially following a redirection of the main ebb channel in 1938 (Findlay and Kirk: 1988), although the delta has remained locationally stable for at least the past two decades.

Hume and Herdendorf's (1992) study of 16 tidal inlets around the east coast of the North Island, using evidence from historical aerial photographs, found that, in general, the overall delta planform and location remained constant over time. This was attributed largely to the prevalence of headlands, protecting the deltas from the effects of variations in wave climate (Hume and Herdendorf: 1992).

2.5 Summary

The morphology found in the vicinity of tidal inlets is very complex. There has been considerable research into tidal inlet stability, due to the importance for navigation. This research has yielded a number of simple relationships that may be used to assess overall stability although these contain inherent weaknesses and may provide erroneous results when applied to other environments.

Comparatively ebb tidal deltas have been subject to much less research because their nature makes them difficult to study. In recent years however, their potential as sources of sediment for industry has increased the need for a greater understanding of their short and long term dynamics. There is still a lack of quantitative data as to short and long term changes in ebb tidal delta systems although considerable work on the United States' east coast, and in New Zealand has shown that the primary controls on ebb delta morphology are tidal prism, shoreline configuration and the wave climate.

Chapter Three: Previous Studies in Southern Pegasus Bay

3.1 Introduction

The Avon-Heathcote estuary is one of the most intensely studied estuaries in New Zealand. Much of the work has had a biological focus with a number of studies being carried out by the Estuarine Research Unit, Department of Zoology University of Canterbury (e.g. Knox and Kilner, 1973). However, the estuary and beaches of southern Pegasus Bay have also been subject to a great deal of investigation, particularly by the staff and students of the Geography Department, University of Canterbury. This chapter will provide a summary of the work that has been undertaken in order to provide a context in which the results from the following three chapters can be placed.

3.2 Geologic History

In geological terms, the present position of the Pegasus Bay coastline is of a relatively recent origin. During the last glaciation, approximately 20 000 years before present, it is generally accepted that the sea level was around 130 metres below its present height and that means that the coastline was 45-50 kilometres east of its present position (Kirk, 1979). Brown and Weeber (1992) reconstructed shoreline positions for southern Pegasus Bay between 10 000 years and 2 000 years before present (B.P.), these are shown in Figure 3.1. Between 9 000 and 6 500 sea level rose rapidly, at a mean rate of around 5.6mm/yr (Suggate, 1958), and the shoreline retreated, reaching a minimum about 10 kilometres west of its present position, 6 500 years B.P. Following this the shoreline prograded rapidly, reaching a point about 4 kilometres west of its present position by 2 000 years B.P and thereafter continued to prograde to assume its present position. This represents a mean rate of progradation in excess of 2m/yr (Wilson, 1976). Kirk (1979) however, points out that since European settlement in the 1850s the shoreline has changed very little which indicates that it is now in long term equilibrium, although it can be expected that there will be short term fluctuations around this equilibrium point.

The Avon-Heathcote estuary, formed as a result of this rapid rise in sea level, has an even more recent origin. MacPherson (1978) suggested that the estuary is no older than 1 000-2 000 years and while Pegasus Bay as a whole is in longterm equilibrium, the mouth of the Avon-Heathcote estuary is one part of the coastline that has been subject to intensive change in the past 150 years.

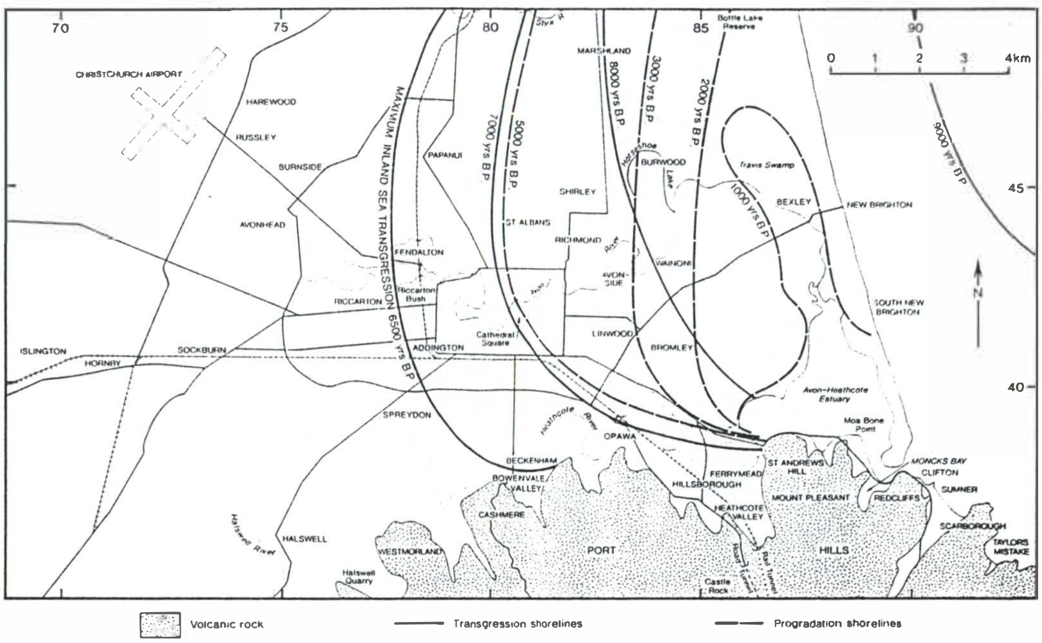


Figure 3.1 Postglacial marine transgression and progradation shorelines.
(from Brown and Weeber, 1992)

3.3 Processes

3.3.1 Wave Climate

Data relating to the local wave climate in Pegasus bay is surprisingly sparse. Burgess (1968) made daily wave observations of wave height, period and direction between December 1967 and May 1968. The longest continuous data set for Pegasus Bay however was gathered by Brown (1976) between November 1975 and August 1976. Recently the Canterbury Regional Council has taken steps to establish a database of wave data for the Canterbury coast and as part of this, daily observations of wave height, period and direction for the mouth of the Avon-Heathcote estuary have been made since May 1994 (D. Todd, Coastal Investigations Officer, Canterbury Regional Council, *pers. comm.*). A somewhat longer data set exists for offshore waves and Reid and Collen (1983) have compiled a summary of observations made from ships for the period 1957-1980.

The wave climate in southern Pegasus Bay is a high energy one (Kirk, 1978) and is characterised by two distinct components (Brown, 1976). Firstly there is long period swell generated from the southerly quarter which is subject to intense modification as it is refracted into Pegasus Bay (Blake 1968; Burgess, 1968). The other component is locally generated wind waves from the east and northeast. These are small and steep with short periods due to the limited fetch over which they propagate.

While there does not appear to be a strong seasonal influence in the wave climate, in general there are more high energy waves from the southerly quarter during winter, although large storm waves may occur at anytime during the year (Burgess, 1968; Brown, 1976; Kirk, 1979). Burgess (1968) for example found that between January and May the incidence of northeast waves declined from 46 percent to 20.8 percent while the incidence of southerly waves increased from 7.6 percent to 37.5 percent. Waves from an easterly direction remained comparatively constant at 46.1 percent (January) and 41.7 percent (May).

In addition to the lower incidence of northeast waves in summer and an increase in the incidence of southerly wave in winter, mean wave period has also been shown to vary between summer and winter. Kirk (1967) observed an increase between February and April from 11.3 seconds to 12.3 seconds, while Burgess (1968) found that period increased from 6.0 seconds in January to 10.0 seconds in May. Brown (1976) found a similar change during her study with period increasing from 7.3 seconds in November to 9.7 seconds in July. It has also been found that there is a corresponding decline in wave steepness with an increase in period. Burgess (1968) for example, recorded a mean deep water wave steepness of 0.015 in January which declined to 0.005 in May.

Analysis of offshore wave data recorded by ships in Pegasus Bay (Reid and Collen: 1983) shows a similar pattern to that of the inshore wave climate. The incidence of waves from the northerly quarter declined from 40.4 percent in summer to 22.2 percent in winter and the incidence of southerly waves increased from 34.7 percent to 53.2 percent. The incidence of easterly waves showed little change with 14.9 percent in summer and 14.3 percent in winter. In should be noted that the incidence of southerly waves was substantially higher and the incidence of easterly waves was substantially lower for the offshore record than for Burgess's (1968) record. The explanation for this is simple, and relates to refraction of waves around Banks Peninsula, so that southeasterly waves arrive at the shore almost completely refracted thereby having an easterly approach as shown in Figure 3.2 (Burgess: 1968).

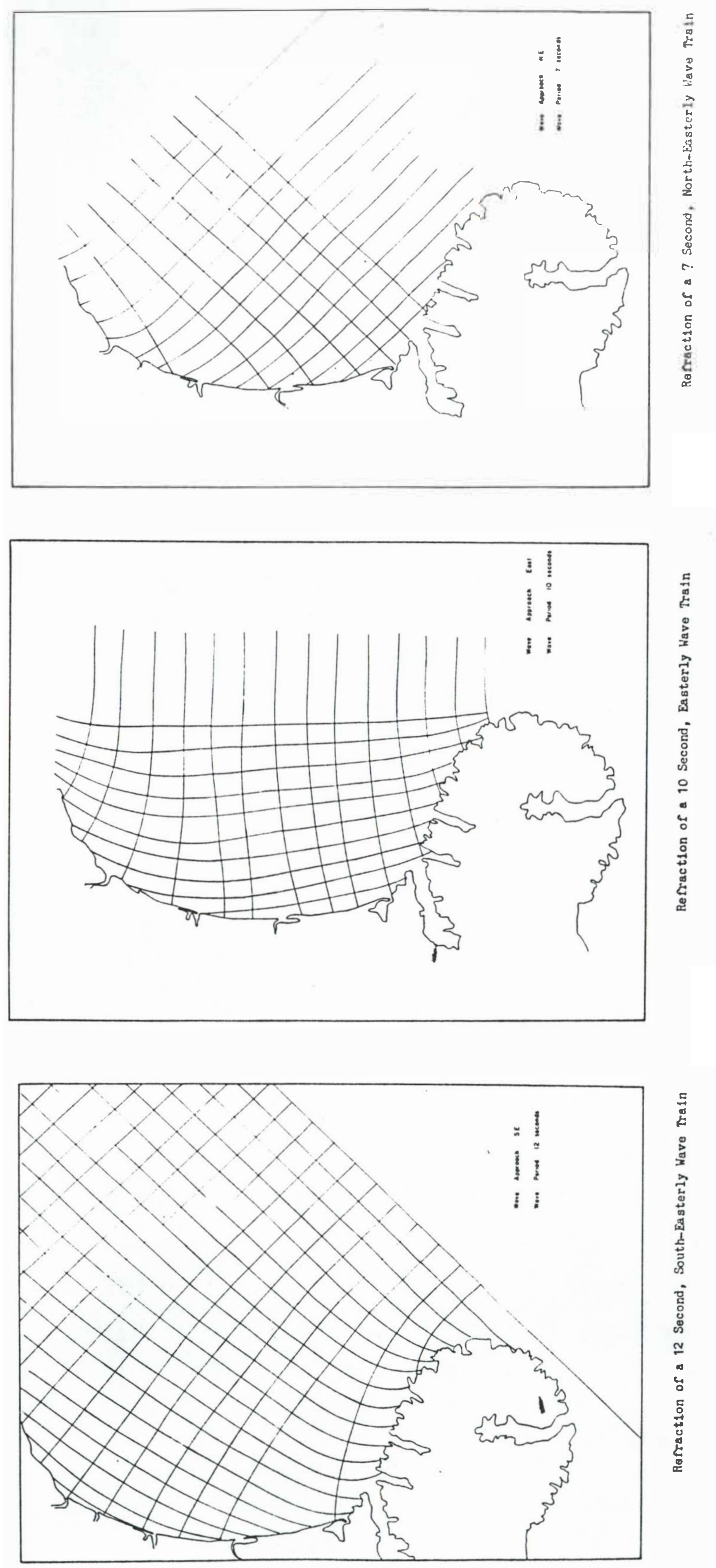


Figure 3.2 Wave refraction patterns in Pegasus Bay
(from Burgess: 1968)

Mean wave period for the offshore data showed absolutely no variation between summer and winter, remaining constant at 7.2 seconds. Part of this can be explained because the inshore data contains a local generated, short period wave component while the offshore data do not. This means during the summer when there is an increased incidence of locally generated northeast waves inshore the mean period is reduced, while the winter figure is higher due to the relatively high frequency occurrence of long period southerly swell. It is interesting however that a mean of 7.2 seconds offshore relates more closely to the summer inshore data when in fact it would be expected to be closer to the winter inshore figure.

While the wave climate is not seasonally dominated, Brown (1976) found a 6-7 day cycle of increased southerly wave activity which she related to the passage of frontal systems over New Zealand. In addition to the short term periodicity identified by Brown (1976), Kirk (1978) suggests that there is evidence that points toward a 10-15 year 'cycle' of southerly storm activity. Analysis of southerly and westerly airflow over New Zealand from 1929-1976 shows that there is a quasi-biennial oscillation of southerly airflow (Trenberth, 1977). This means that in alternating years there will be relatively more southerly airflow than northerly and vice versa. The prevalence of westerly airflow however, follows a 2-6 year oscillation (Trenberth, 1977). These two patterns coincide every 10-15 years and result in sustained periods of high energy storm waves in Pegasus Bay (Kirk: 1978). Kirk (1978) therefore suggests that during periods of increased southerly activity it can be expected that erosion and accretion will be superimposed on a generally eroding trend. Conversely during periods of increased westerly airflow, phases of accretion and erosion will be superimposed on a generally accreting trend.

3.3.2 Tides

Tides on the Canterbury coast are somewhat unusual in that they do not follow the usual fortnightly cycle of springs and neaps (Goring, 1991). Generally speaking spring tides occur when the sun and moon are aligned in a straight line with the semi-diurnal lunar tide (M2) and the solar tide (S2) coinciding to give a maximum tidal range. Neap tides occur when the sun and moon are at right angles and the reduced gravitational attraction give a minimum tidal range. On the Canterbury coast however, the solar tide (S2) seems to have relatively little influence on the tides, with an amplitude of only 46 millimetres at Lyttelton, so the fortnightly cycle between springs and neaps is not strongly pronounced (Goring, 1991). Rather the tidal cycle follows roughly a monthly pattern reflecting the influence of the lunar elliptic (N2) tide which has an amplitude of 200 millimetres, and M2 tide which has an amplitude of 876 millimetres (Goring: 1991). Maximum tidal range therefore occurs when the moon is closest to Earth and the gravitational attraction is at its greatest (perigee). Conversely when the moon is furthest from Earth (apogee), minimum tidal ranges result. This follows roughly a 28 day cycle, although every seven months perigean tides coincide with spring tides giving exceptionally high and low tides (Goring, 1991).

Analysis of tide data recorded at the Ferrymead Bridge shows that perigean tides have a range of approximately 2.1 metres while apogean tides have a range of 1.1 metres (Knox and Kilner, 1973). From examination of the Ferrymead Bridge data for the period 1968-1980, Oliver and Kirk (1992) determined extreme water levels in the Avon-Heathcote estuary and found that barometric lift and wind and wave set up can also have a significant effect on water levels in estuary. For example, Table 3.1 shows that during the storm of January 17-18, 1980, the combined effects of barometric lift and wind and wave set-up elevated water levels in the estuary by 0.82 metres (Oliver and Kirk, 1992).

Date	Max. Height (m)*	Elevation above MHWS (m)	Baro. Lift (m)	Wind Set-up (m)	Wave Set-up (m)	Wave Height (m)	Wave Period (secs)
10-12 Apr 1964	1.60	+0.29	+0.23	+0.30	+0.11	0.68	2.50
28 Jun 1977	1.57	+0.26	+0.28	+0.005	+0.07	0.45	1.85
4 Jul 1977	1.72	+0.41	+0.21	+0.30	+0.11	0.68	2.50
24 Jun 1978	1.77	+0.46	+0.14	+0.07	+0.06	0.40	2.00
20 Jul 1978	1.75	+0.44	+0.18	+0.04	+0.06	0.38	1.75
2-3 Jan 1980	1.55	+0.24	+0.16	+0.67	+0.12	0.75	2.75
18-18 Jan 1980	1.73	+0.42	+0.42	+0.30	+0.11	0.68	2.50

* Height above MSL (CRC Datum)

Table 3.1 Extreme Water Levels at Ferrymead Bridge (after Oliver and Kirk, 1992)

Heath (1976) calculated tidal prism for the Avon-Heathcote estuary and found that the volume for springs and neaps were 11 x 10^6 m^3 and 6 x 10^6 m^3, respectively. As already pointed out however, the Canterbury coast does not experience true spring and neap tides so presumably Heath's (1976) estimates in fact relate to perigean and apogean tides. Hastie (1979) found that maximum discharge through the main outlet channel on the flood tide was 1.18 m/sec. This occurred around mid-tide although Hastie (1979) does not specify at what stage in the monthly tidal cycle his study was carried out. It would however be reasonable to assume that it was probably near perigee as his estimates of tidal prism closely approximate the value calculated by Heath (1976) for spring tides. Hastie's (1979) maximum velocity can be compared with those determined by the Wallingford Report (1970) which gave the flood tide maximum as 1.5 m/sec. and the ebb tide maximum as 1.8 m/sec.

3.3.3 Freshwater Input

The Avon-Heathcote estuary takes its name from the two main rivers which drain into it. The catchment area for the Heathcote (105.2 km^2) is approximately 20 percent larger than the Avon (83.7 km^2) (Millward: 1975), although the Avon River has a higher mean flow (3.25 cumecs) than the Heathcote River (1.13 cumecs) (Mawson: 1972). During flood conditions however, the Heathcote River experiences greater flows due to run off from the Port Hills. Maximum discharge for a 50 year event was calculated by Mawson (1972) to be 79.30 cumecs for the Heathcote and 52.96 cumecs for the Avon.

Based on these flow rates it can be see that under mean flow conditions, the Avon and Heathcote rivers make a relatively small contribution to the tidal prism. Their combined discharge over one half tidal cycle (6.25 hours) is just over 1 x 10^5 m^3, or approximately 1 percent of tidal prism. Under flood conditions however the contribution can become very significant. Based on the 50 year event data (Mawson: 1972) for example, discharge over a half tidal cycle would be approximately 3 x 10^6 m^3, or 27 percent of tidal prism.

3.4 Sediments

3.4.1 Coastal Sediments

Much of the sediment in southern Pegasus Bay is derived from the Waimakariri and Ashley rivers to the north. Kirk (1979) estimates that the Waimakariri River supplies some 650 000 m^3 of coarse sand to Christchurch beaches each year. It has also been found that the mineral composition of sediment found near Sumner indicates that the supply of sediment from Banks Peninsula is negligible (Scott, 1955). A number of studies (e.g. Reed, 1951; Blake, 1968; Kruger, 1980) have shown that sediment found in the vicinity of the mouth of the Avon-Heathcote estuary is well sorted, fine sand.

The sediment near the mouth of the Avon-Heathcote estuary is derived from the rivers to the north and transported along the coast under littoral drift processes. Brown (1976) determined through tracer experiments that there was an annual gross transport rate of 978 000 m^3 although the net drift was only 74 000 m^3 in a northward direction. It can be seen then that while there are relatively large total amounts of sediment being transported the net change is relatively small. Net transport, in any year, may be in either direction although southward transport is more likely during summer and net northward transport is associated with years which have increased southerly activity (Kirk, 1979).

3.4.2 Estuarine Sediments

The Avon and Heathcote rivers deposit 2 600 t/yr and 4 500 t/yr respectively in the estuary (Hicks, 1993) and there is a tendency for this sediment to be subsequently transported toward the mouth of the estuary with sediment size decreasing with distance from the river mouths (Kruger, 1980). In the immediate vicinity of the mouth of the estuary however, both Kruger (1980) and Millward (1975) found a reversal of this. Sediment size increased with distance from the mouth into the estuary which reflects that the coast is also a source of deposition within the estuary (Millward: 1975).

A number of studies have examined net sedimentation in the estuary and have yielded different results. Pearse (1950) suggested that in the decade up to 1950 there had been a considerable build-up of sediment in the estuary, while MacPherson (1978) found that during his study the estuary was a net exporter of sediment. Kruger's (1980) study only two years later found the estuary was a net exporter of sediment but attributed this reversal to high incidence of southerly activity during the preceding two years (Kruger: 1980). These studies were all made over short time periods and Hicks (1993) found that between 1962 and 1975 sediment was removed from the estuary at a mean rate of 2-3 mm/yr but since 1975 there has been a slow build up of 1 mm/yr, when volumes are averaged over the whole estuary. This would seem consistent with both Pearse (1950) and MacPherson (1978) and that Kruger's (1980) findings were only a temporary reversal. This suggests that sedimentation in the estuary is in long term equilibrium although in the short term the volume of sediment stored in the estuary may vary.

3.5 Changes at the Mouth of the Avon-Heathcote Estuary since 1850

In the early days of Canterbury settlement, during the latter half of last century the estuary and Avon and Heathcote rivers were used extensively as a means to transport cargo into Christchurch. Several times it was proposed to dredge the estuary and the Heathcote River to facilitate a port development at what is now known as Opawa. As a consequence of this, there is extensive data, in the form of maps and soundings, about the mouth of the Avon-Heathcote estuary, although in the past two decades no soundings have been carried out.. Supplementing these with old photographs and paintings, several authors have been able to construct relatively detailed maps of changes that have occurred at the mouth of the Avon-Heathcote estuary since the 1850s (MacPherson, 1978; Findlay, 1984; Findlay and Kirk; 1988).

Figure 3.3, compiled from vertical aerial photographs, presents a summary of the changes that occurred at the mouth of the Avon-Heathcote estuary between 1940 and 1993. In addition to this Figure 3.4 shows changes to the spit between 1847and 1930 and Figure 3.5 illustrates the location of the ebb tidal delta between 1854 and 1993.

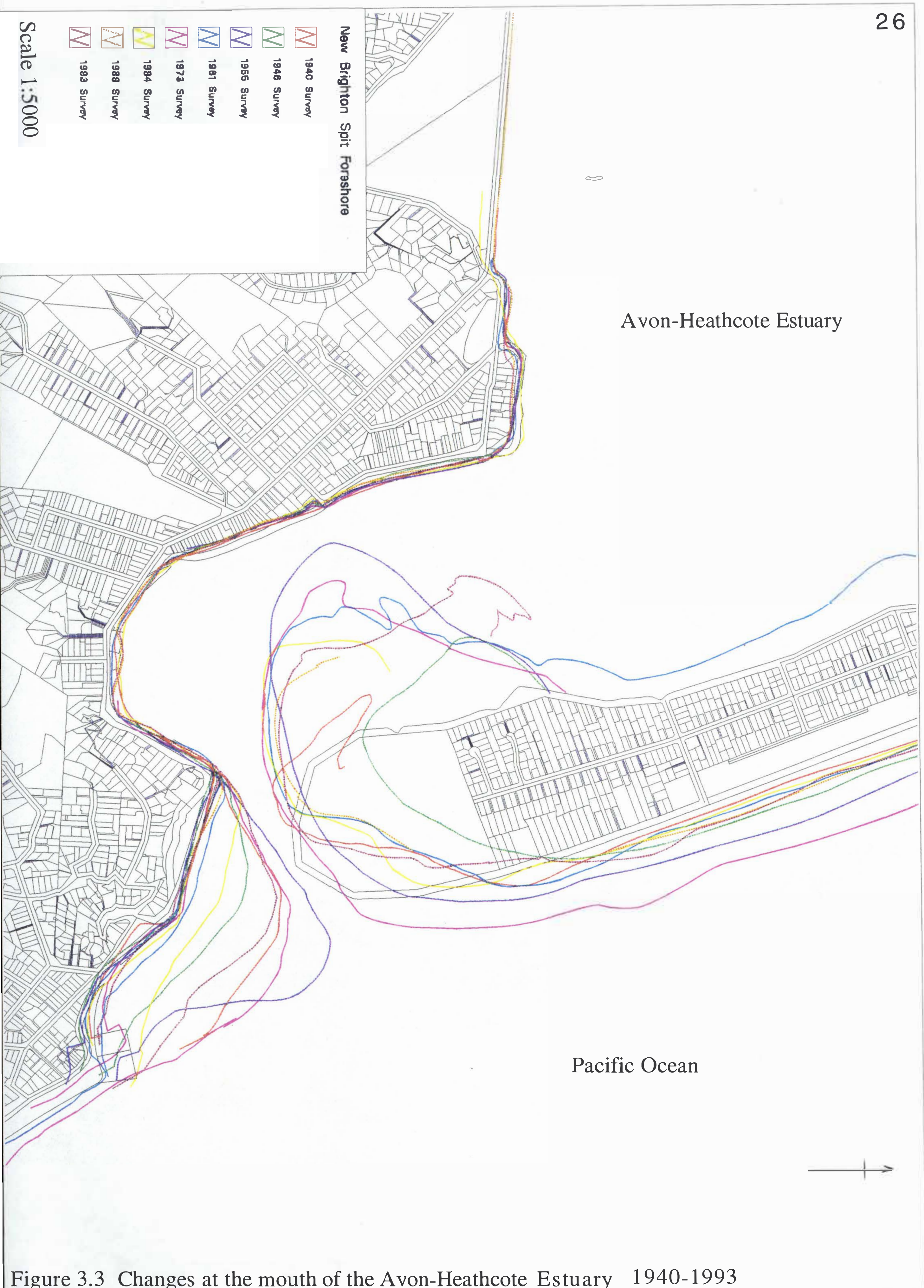


Figure 3.3 Changes at the mouth of the Avon-Heathcote Estuary 1940-1993

(Compiled by M. King, Canterbury Regional Council)

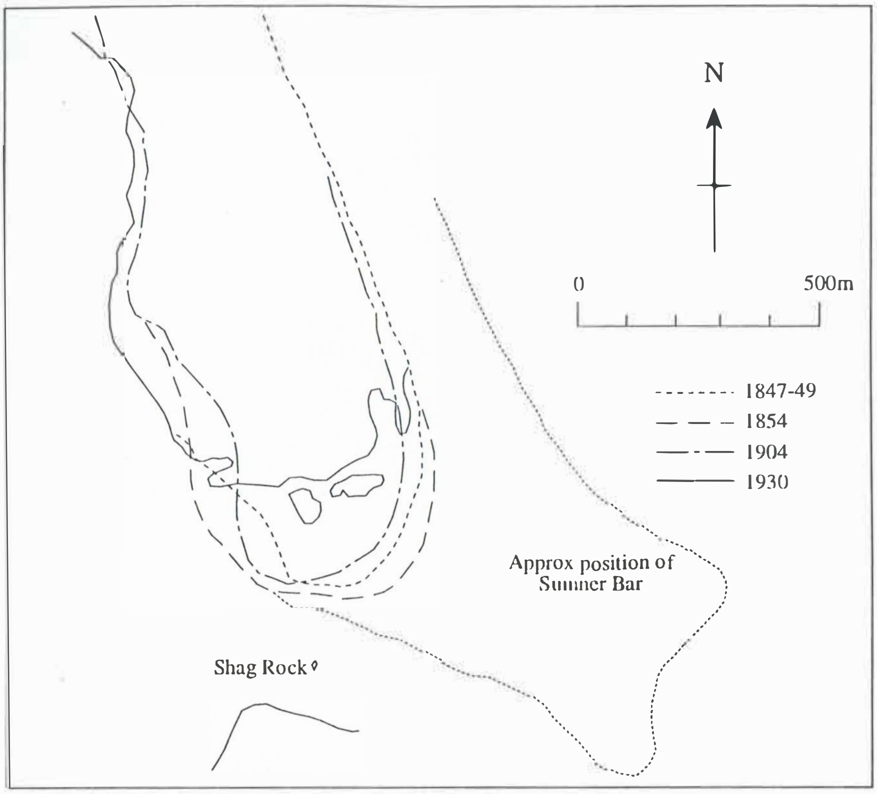


Figure 3.4 Changes to the spit tip between 1847 and 1930.
(redrawn from Finlay and Kirk 1988)

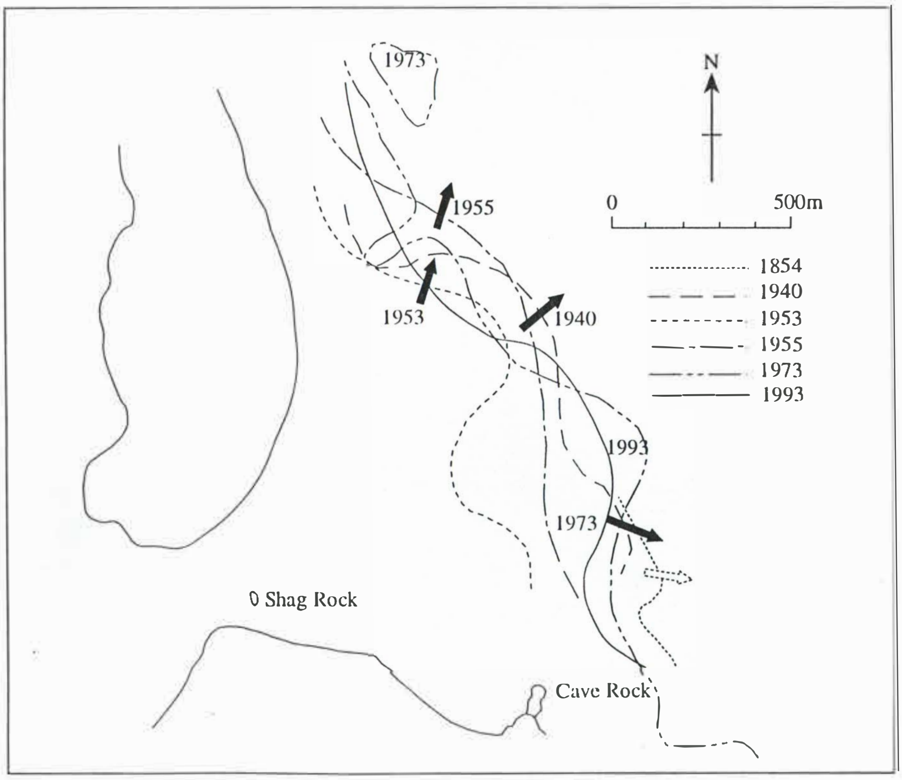


Figure 3.5 Extreme positions of the ebb tidal delta, 1854 -1993.
Arrows show outflow of respective ebb tide channels
(after Findlay and Kirk: 1988)

3.5.1 South Brighton Spit

Findlay and Kirk (1988) suggested that there were three periods of erosion at South Brighton between 1918 and 1949. The first was 1918-1922 when the spit tip lost almost nine hectares to erosion (Pearse: 1950). Sporadic erosion then occurred between 1930 and 1937. The most significant erosion of the spit tip however occurred in the period 1940-49, where the spit eroded 500 metres (Figure 3.3). This phase of erosion caused considerable concern to local ratepayers, particularly in 1948 when storm seas breached the inner line of dunes (Findlay, 1984). This prompted the construction of a groyne, initially in the form of sandbags, but this was later extended in the 1950s with the construction of a drum groyne and a brushwood fence system. It was also during this period between the 1920s and 1950s that the spit developed it characteristic hook, which has been maintained up until the present. Although there were brief periods of localised erosion, the period from the early 1950s until 1977 was generally characterised by accretion of the spit tip, although during the 1980s and up to 1993, the spit tip showed an eroding trend (Figure 3.3).

3.5.2 Clifton Bay

Between 1849 and 1980, Findlay and Kirk (1984) have identified 3 periods of erosion and 3 of accretion in Clifton Bay. The period 1849-1907 was generally characterised by erosion, and throughout this period, the high tide shoreline was close to the cliffs around the base of Clifton Hill (Pearse: 1950). Between 1907 and 1923, Clifton Bay accreted with sand building up at Cave Rock and also under the pier. There was a short phase of erosion between 1923 and 1927 with significant erosion, caused by storm waves, occurring in 1924,1925 and 1926 (Pearse, 1950). From 1927, there was a long period of accretion (Pearse, 1950) continuing up until the early 1950s (Figure 3.3). Clifton Bay extensively filled with sand both by natural and artificial means, and by 1950 the high tide shoreline in the centre of Clifton Bay had shifted 275 metres seaward (Pearse, 1950).

Erosion began again in 1952 and continued until the middle of the 1960s. The sandhills that had formed were removed by storm waves during 1954 and it was not until 1968 that small vegetated dunes began to reappear on the beach (Findlay and Kirk, 1984). Accretion continued for the next decade until it was interrupted by extensive storm activity during the period 1978-1980. since the early 1980s, Clifton Bay has generally accreted, with dunes developing in the area between the surf club and Cave Rock. This accretion has been encouraged with planting and the construction of fences by the Christchurch City Council.

3.5.3 Ebb Tidal Delta System

Prior to 1938 the main ebb channel flowed southeast past Shag Rock into Clifton Bay and was then diverted northwards in the vicinity of Cave Rock (Pearse, 1950, Findlay and Kirk, 1988). Also prior to 1938 there was a large sandbank, which became exposed at low tide, that extended from the spit, south to Cave Rock (Findlay and Kirk, 1988).

In 1938 the main ebb channel changed its orientation from southeast to an easterly strike. This was first noticed in June 1938 after a high tide, although it is significant that the shift was not the result of storm activity (Rule, 1980 in Findlay and Kirk, 1988). Findlay and Kirk (1988) also suggest that this marked a change from a bar bypassing regime to a tidal bypassing regime.

The positions occupied by the seaward margin of the ebb delta between 1854 and 1993 are shown in Figure 3.5. The 1940 position shows the delta 750 metres further north than what it was in 1854. Between 1940 and 1955 the delta migrated further north but by 1973, the margin was well to the south, occupying approximately the same position as it did in 1854. Since 1973 the delta margin has remained in basically the same position, 1 000 metres northeast of Shag Rock.

The beaches of South Brighton and Clifton Bay and the ebb tidal delta have been shown to be highly variable since the 1850s. Generally speaking however, periods of erosion at South Brighton have been reflected by accretion in Clifton Bay and *vice versa* (Figure 3.3). The pattern seems to be intimately related to the position of the ebb tidal delta. Wave energy is expended on the delta so when it is located to the north, the tip of the spit receives some protection from storm waves while Clifton Bay is relatively exposed. Conversely, when the delta occupies a southerly position, the spit becomes relatively exposed while Clifton Bay is protected from erosive storm waves.

Changes at the mouth of the Avon-Heathcote estuary can also be linked to increases in tidal compartment since 1850 (MacPherson, 1978; Findlay and Kirk; 1988) as shown in Figure 3.6. While Findlay and Kirk (1988) demonstrated that MacPherson (1978) made errors in some of his calculations, there is a clear relationship between increased runoff into the estuary due to urbanisation and an

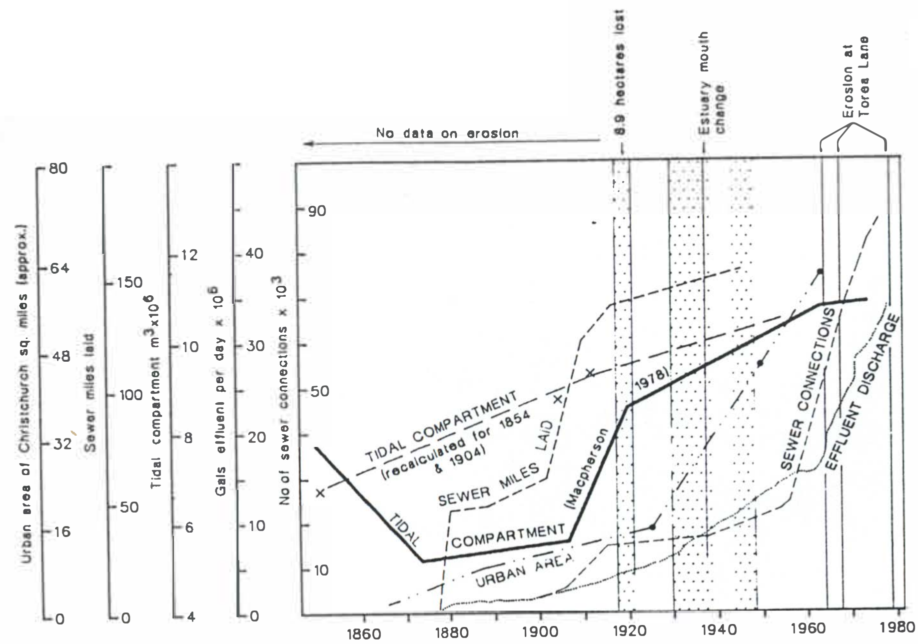


Figure 3.6 Tidal compartment, sewer miles laid, sewer connections made, urban area from 1850 to 1981. Periods of erosion srippled; crosses show Findlay and Kirks (1988) recalculated tidal compartment.
(from Findlay and Kirk: 1988)

increase in tidal prism. Both calculations show a steady increase in tidal prism since 1920 with no dramatic change associated with the sudden movement of the main ebb channel in 1938. It is however possible that in June 1938 tidal prism reached a critical volume forcing the change in direction of the channel and this is consistent with the fact that it was first observed following a high tide rather than a storm event. The change in the bypassing regime in 1938, from bar to tidal (Findlay and Kirk: 1988), is also consistent with this, as predicted by Bruun and Gerritson (1960). Oliver and Kirk (1992) however also note that 42 percent of the increase in tidal prism can be explained by the steady rise in sea level this century described by Hannah (1988).

3.6 Summary

The Avon-Heathcote estuary is relatively young in geological terms with Brighton spit being no more than 1 000-2 000 years old (MacPherson: 1978). The mouth of the estuary is modified by the high energy wave environment, with erosion being linked the passage of frontal systems which have a periodicity of 7-9 days (Brown: 1976). Kirk (1978) also identified a 10-15 year cycle of significant southerly storm activity. The tidal regime is also influential, and this operates on a monthly cycle with perigean tides having a one metre greater range than apogean. This leads to large fluctuations in tidal prism during the monthly cycle and therefore variations in the velocity of currents flowing through the estuary mouth.

The beaches and delta at the mouth of the Avon-Heathcote estuary have been shown to fluctuate dramatically but there appears to be a relationship between erosion at South Brighton spit and accretion in Clifton Bay. This pattern also seems to be related to the location of the ebb tidal delta.

Chapter 4: Morphological Change at South Brighton Spit and Clifton Bay

4.1 Introduction

There are two distinct beach systems at the mouth of the Avon-Heathocte estuary (Figure 4.1). North of the inlet channel is the beach associated with the distal end of South Brighton Spit. At the estuary mouth the spit is approximately 300-400 metres in width. Urban housing is located within 500 metres of the main inlet channel to the south and within less than 100 metres of the active beach system to the east. The southern extreme of the spit tip is well vegetated with grasses and shrubs and in addition to this there are a number of relatively large pine trees, up to about 15 metres in height. In some cases these are within 20 metres of the active beach system, suggesting that the bulk of the spit tip is relatively stable in the short and mid term.

For the greater part, South Brighton spit is orientated southeast although 500 metres from the inlet channel the spit suddenly curves and has a south-southeast orientation. The foreshore in the area of the spit tip is typically around 100 metres in width, and is backed with small foredunes, around 2-3 metres in height although these are periodically broken by scarps, reflecting short term erosion. The small foredunes in this area are in sharp contrast to the large, 5-10 metre, dunes found further to the north. Offshore from the spit tip is a large ebb tidal delta although north of the study site, this grades into an offshore bar systems which continues, almost continuously, along the length of Pegasus Bay.

In contrast to the spit tip, the beach in Clifton Bay is orientated northeast and the foreshore is variable in width, being 50-60 metres wide in the vicinity of Shag Rock increasing up to 200-300 metres in width towards the southeastern end of Clifton Bay. The foreshore is backed by a rock revetment which extents about 500 metres south from the estuary mouth and thereafter is backed by a low wall. There is therefore, very little backshore in Clifton Bay, although in the past decade dunes have begun to form on the beach to south near Cave Rock and these have been encouraged with fencing and planting of marram grass by the Christchurch City Council. The boundaries of Clifton Bay are demarked by the main inlet channel to the north and by Cave Rock to the south. Cave Rock, which is around 80 metres in length and extends in the sea, acts as a natural groyne and impedes the transport of sediment to Sumner Bay, immediately south of Cave Rock.

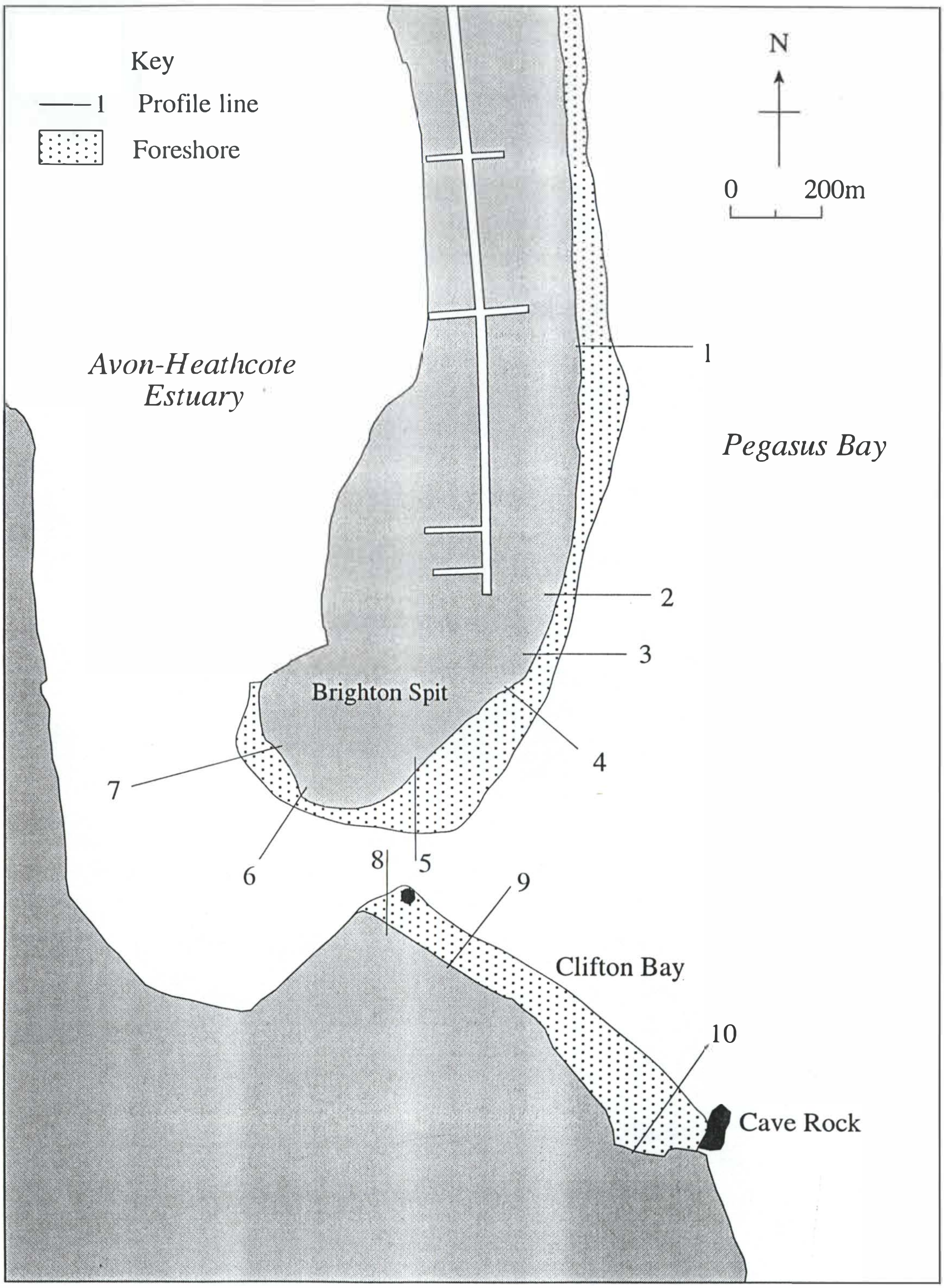


Figure 4.1 Location of profile lines

Both beaches typically have relatively flat foreshores, with gradients of around 1:100, reflecting their composition of fine to medium sands. The sediments in the vicinity of the Avon-Heathcote estuary mouth are also well sorted, having been extensively reworked during transport from their main source in the Waimakariri River, 40 kilometres to the north (Blake 1964).

This chapter examines the morphological changes in the beaches described above, between November 1993 and August 1994. It presents data gained from 10 profile sites (Figure 4.1) surveyed at monthly intervals. For each site the same data is presented in three ways. Firstly the data is plotted as a profile line on a graph. This form of presentation represents the data in its least simplified form, although a consequence of this is that it is difficult to absorb the large amount of information being presented. In order to make analysis and interpretation easier the data are secondly, expressed in terms of volume under the profile line and then thirdly, in terms of excursion distance. For each site a description is made of the salient changes between surveys and then in section 4.5 the relationships between the profile sites are discussed. The processes responsible for the morphological changes presented in this chapter will not be discussed until Chapter Seven so that rather than being discussed in isolation, the changes occurring at the beach can be viewed in conjunction with those which occurred to the ebb tidal delta.

4.2 Methods

4.2.1 Profiles

In order to measure beach change at the mouth of the Avon-Heathcote estuary, 10 profiles were surveyed on a monthly basis. The profiles extended from Torea Lane in the north to Cave Rock in the south, as shown in Figure 4.1. Profile One, at Torea Lane, has been surveyed intermittently by the staff and students of the Geography Department, University of Canterbury since 1964. Profiles Two, Eight and Ten are part of a network of profile lines that the Canterbury Regional Council established in 1990. They have been surveyed since May 1990 at approximately six monthly intervals and therefore provide a longer term context in which the results of this study can be placed. The remaining six profile lines were all temporary established in November 1993, with the exception of Profile Nine, which was established in December 1993. These temporary profile lines were placed according to two criteria. Firstly they filled the gaps between the existing 'permanent' profiles and secondly they were placed where there were visible differences in the state of the backshore, such as the presence or absence of foredunes.

Profiles were surveyed from a bench mark in the backshore down to at least one metre below mean sea level and were carried out using a Sokkia SET4BII Total Station theodolite.

4.2.2 Calculating Beach Volume

The volume of sediment in each profile was determined using a Microsoft *Excel* spreadsheet. Total volume, expressed in cubic metres per metre of beach (m^3/m), was calculated as the area under the profile line, taken from the bench mark down to one metre below mean sea level. In addition to total volume, the volumes of sediment in the backshore and foreshore were also determined.

Kirk (1979) defines the backshore as the zone which extends from the upper limit of swell wave swash, inland to the dunes or cliffs. The foreshore is defined as the area between the swash berm crest (or the upper limit of swell swash at high tide) and the ordinary low water mark. Using the data gained from this study, the position of the mean high water mark (which approximates the interface between the backshore and foreshore) lay at approximately 1.7 metres above mean sea level and the mean low water mark at approximately 0.6 metres below mean sea level. When calculating volumes, these were rounded to 2.0 metres and -1.0 metres respectively to make them consistent with the contour intervals used in the excursion distance analysis.

On some profiles there were more than one 2.0 metre and -1.0 metre contours. In these cases the most seaward of each was taken for the purposes of calculating volumes. Where the profile did not extend as far as the -1.0 metre contour, as was the case with some of the Canterbury Regional Council, the line was extrapolated.

4.2.3 Excursion Distance Analysis

Excursion distance analysis (EDA) makes it possible to view a large quantity of profile data in both a spatial and temporal context (Winton, Chou, Powell, and Crane, 1981). Plots are constructed using time along the x-axis and distance of vertical contours, from a reference point, along the y-axis. From each contour line it can be seen whether the beach is eroding or accreting. A negatively sloping line indicates erosion, while a positively sloping line indicates accretion. In each instance the gradient of the line shows the rate of change. As with other contour maps, the distance between contours shows the gradient of the beach. In addition to this, the distance between contours can also be used to make crude estimates of beach volume.

For this study EDA was performed on the -1.0, 0.0, 1.0 and 2.0 metre contours. One of the purposes of performing EDA on the profiles was to determine where on the profile waves would break. At low tide waves typically broke around the seaward -1.0 metre contour and did not usually reform. At mid and high tide however waves would progress onshore and did not generally break until they were past the most landward negative one metre contour. Therefore in instances where there was more than one, -1.0 metre contour, the most landward contour was used. As in the case of the volume calculations, the most seaward contour was used where there was more than one, 2.0 metre contour profiles. There were no cases where there were multiple 1.0 or 0.0 metre contours.

4.3 Beach Cycles and Typical Profile Characteristics

Before the beach profile data is presented it is useful to briefly summarise the literature relating to beach cycles and profile characteristics, to provide a comparison of those observed during this study.

It is a well established notion in the literature that beaches undergo their most rapid and extensive change during high energy events (e.g. Sonu and van Beek, 1971; Chappell and Eliot, 1979; Aubrey and Moss, 1985; Sallenger, Holman and Birkemeier, 1985). Beaches adjust there profile configuration to reflect the processes acting on it. In general, after extended periods of swell, the beach profile will accrete and berms commonly form on the foreshore and the profile becomes steeper. During storms, sediment is removed from the foreshore and deposited on nearshore bars and the beach becomes flatter. These two scenarios, as shown in Figure 4.2, are often incorrectly referred to as 'summer' and 'storm' profiles, which reflects the often incorrect assumption that swell waves occur during summer and storm waves during winter.

The swell/storm profile model is the most simple of those describing beach cycles and numerous other studies have provided models which contain intermediate stages between swell and storm profiles (e.g. Hayes, 1972; Sonu and van Beek, 1971; Sonu, 1973; Chappell and Eliot; 1979). For example Sonu and van Beek (1971) present a 12 stage model relating to combinations of profile configuration (convex, linear or concave) and berm location (lower berm, intermediate berm, upper berm or no berm). Chappell and Eliot (1979) present a model of beach cycles for Australian beaches determined by wave climate and nearshore cell circulation. Theirs is similar to Sonu and van Beek (1971) although this model includes offshore bar characteristics (continuous, discontinuous, bar gap or transverse bar) rather than berm characteristics.

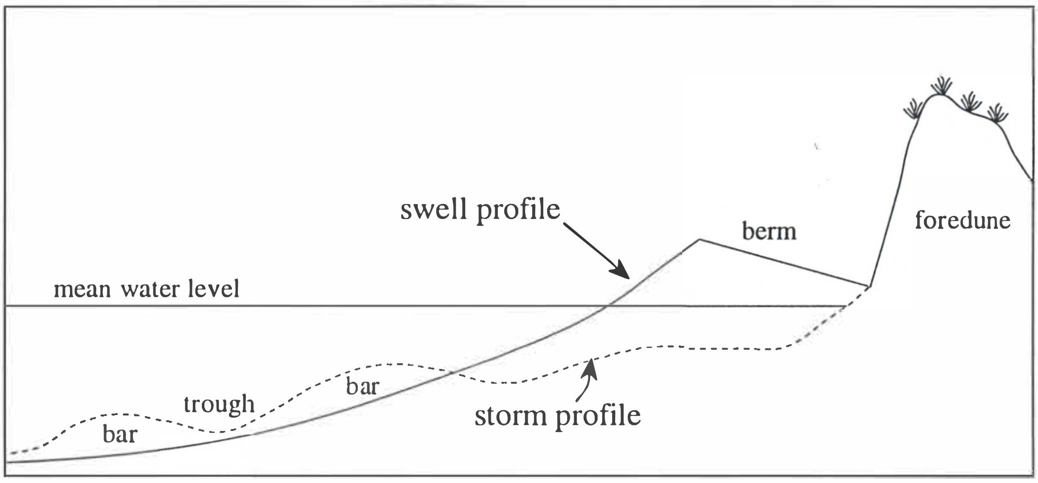


Figure 4.2 Characteristic swell and storm beach profiles
(after Komar: 1976)

Beach cycles however are more complex than this and erosion and deposition at the shore is a reflection of not only the wave climate and longshore currents, but also the wind climate, the nature of storm activity, sediment grain size and sorting, and the nature of the offshore topography. This latter point is particularly important when considering the beaches adjacent to the Avon-Heathcote estuary mouth due to the presence of the ebb tidal delta. This acts like a natural breakwater, modifying waves before they reach the shore. This is particularly important during storms where much of the wave energy is dissipated over the delta. Unlike a simple offshore bar however, the delta is not removed and persists at the estuary mouth throughout periods of both 'storm' and 'swell' activity.

It has also been demonstrated by several studies in Southern Pegasus Bay, that the occurrence of southerly storm waves do not exhibit a seasonal periodicity (Burgess, 1968; Brown, 1976) although periods of erosion have been linked to the 7-9 day cycle of frontal systems over New Zealand (Brown, 1976). Kirk (1978) also identified a possible longer term periodicity of severe erosion relating to the coincidence of increased westerly and southerly activity every 10-15 years.

4.4 Change in Beach Profiles

4.4.1 Profile One

This profile was first established in 1964 in order to monitor the beach following severe erosion as a result of a southerly storm (Kirk, 1978). The bench mark for this profile was taken from a concrete block on the northeast corner of the most northerly of the three houses at this site. Directly in front of the houses was a two metre high, well vegetated scarp. A hollow separated this scarp from a small (one metre) dune that had its base three metres above mean sea level and was well vegetated with ice plant.

As shown in Figure 4.3a, this profile exhibited very little change throughout the study period. Berms developed in the backshore in February and June, but in both cases were subsequently removed prior to the next survey. In Figure 4.3b it can be seen that the backshore volume remained relatively constant with any variations being less than 10 m^3/m. Throughout the same period the foreshore both eroded and accreted but again variations were small and did not exceed 20 m^3/m. The excursion distance plot (Figure 4.3c) reveals that, overall, the -1.0 metre and 0.0 metre contours moved landward, but by only 30 metres and 15 metres respectively. The one metre contour also showed a slight eroding trend but this was punctuated by the seaward movement between May and June, reflecting the development of a large berm in the backshore. The two metre contour showed virtually no movement apart from slight shifts seaward in June and August.

These results can be also be viewed in a longer time frame as shown in Figure 4.4. The first plot displayed in Figure 4.4a was surveyed in 1964 and shows the beach in a grossly eroded state. Following this the beach accreted (Kirk, 1978) but the surveys taken in the late 1970s again show the beach in an eroded state. There is then a 10 year gap in the data although the excursion distance plot (Figure 4.4c) shows that the beach had experienced net accretion between the 1978 and 1992 profiles. Since then, and throughout this study period however, the beach displayed an eroding trend. From Figure 4.4b it can be seen that between 1977 and 1994 there have been large fluctuations in beach volume, both in the foreshore and backshore.

Figure 4.3 Profile 1

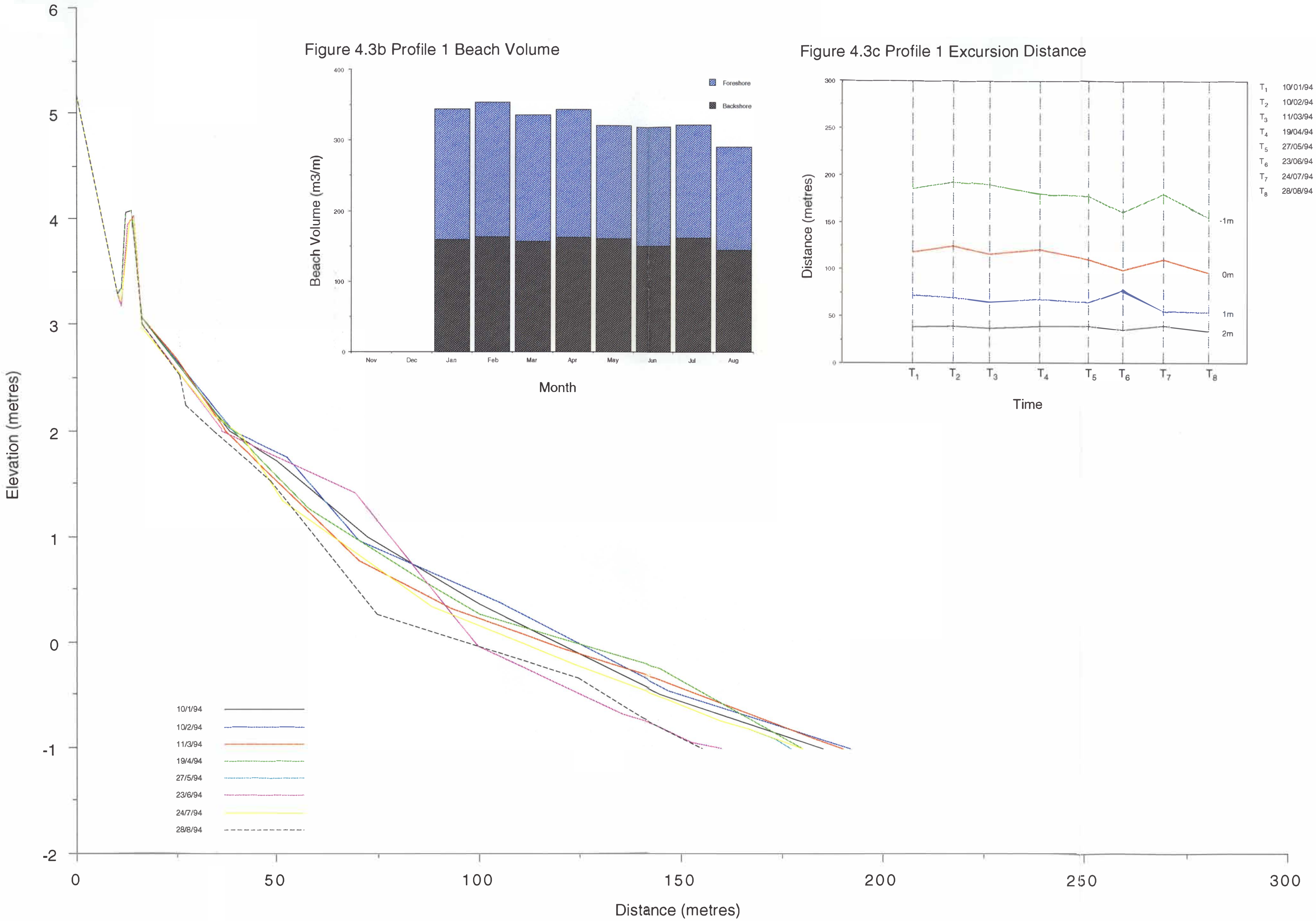


Figure 4.3a Profile 1 Plot

Figure 4.3b Profile 1 Beach Volume

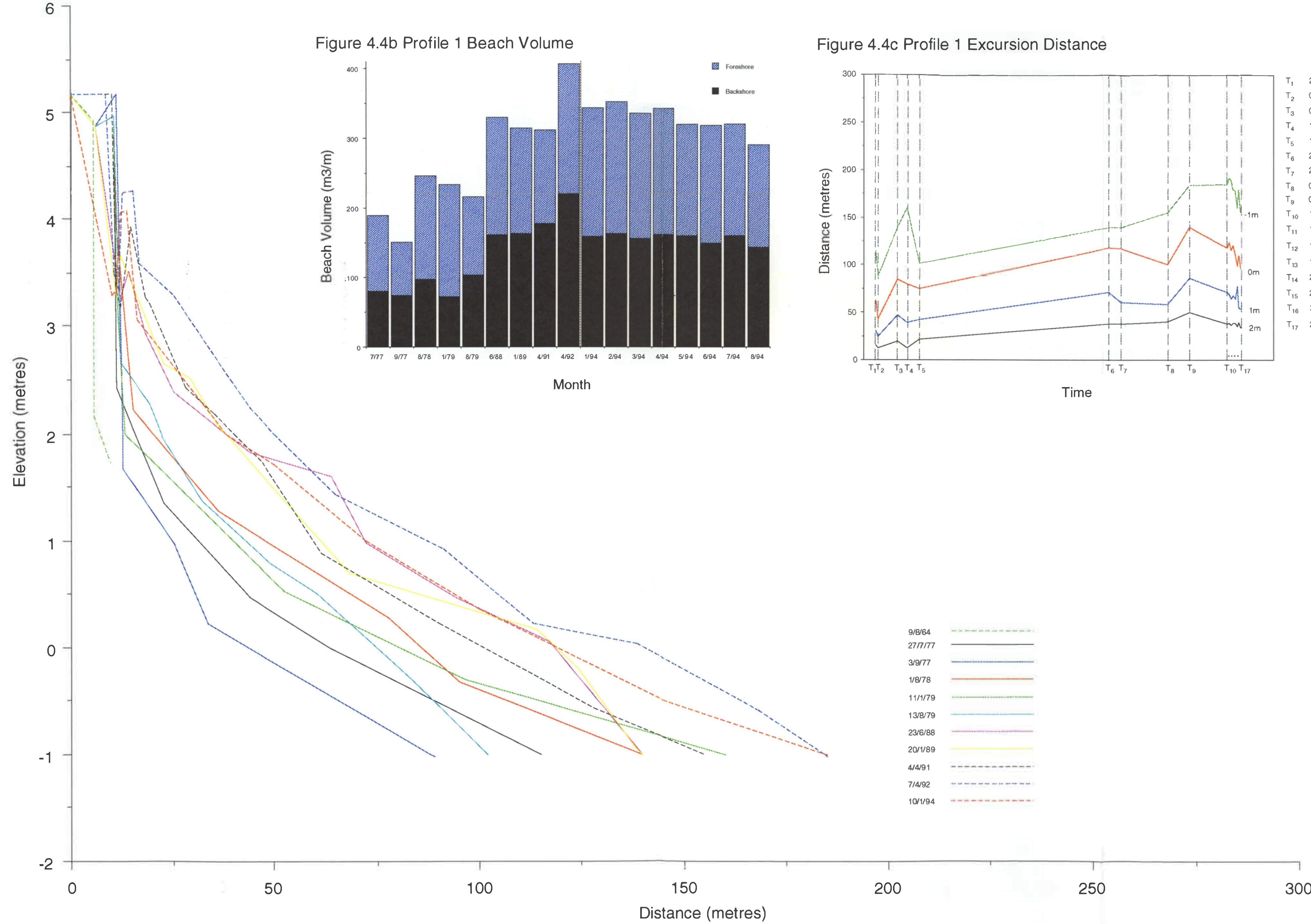
Figure 4.3c Profile 1 Excursion Distance

Figure 4.4 Profile 1 1964 - 1994

Figure 4.4a Profile 1 Plot

Figure 4.4b Profile 1 Beach Volume

Figure 4.4c Profile 1 Excursion Distance



Rapid periods of recovery in the foreshore followed periods of erosionduring the late 1970s and the backshore accreted substantially particularly between 1988 and 1992, reaching a peak in 1992 of 220 m^3/m, three times the July 1977 volume. Between 1992 and 1994 the backshore eroded while the quantity of sand stored in the foreshore remained consistently higher throughout 1994 than for any other period.

4.4.2 Profile Two

This profile runs due east, perpendicular to the end of Rockinghorse Road and was established by the Canterbury Regional Council in May 1990. The benchmark for this profile is located on top of the second dune. The foredune crest reached a height of just over five metres although the front face has been cut away leaving an approximately three metre high scarp. The foreshore was approximately 100 metres in width and with the base of the scarp at about 2.2 metres, swash only extended this far up the beach during perigean tides.

The first survey plotted in Figure 4.5a shows that in January 1994 there was a relatively steep foreshore extending into a channel that remained filled with water even at low tide. Seaward of this point it can be seen that a large slug of sediment, representing 115 m^3/m of sediment, was moving onshore. By February this had completely welded onto the beach and the profile took on a concave shape which persisted throughout the study period. Little changed occurred in this profile until May when high seas cut the scarp back and also formed a berm high up the beach, at a height of two metres above mean sea level. This berm had been removed by June but reformed during July and then also persisted throughout August.

Throughout the study period, with the exception of January, the foreshore exhibited little change. The foreshore lost approximately 40 m^3/m between January and February as the slug of sediment welded itself to the beach and the profile returned to a more equilibrium form. The maximum variation in the volume of sediment in the foreshore between any of the other months was 15 m^3/m between March and April (Figure 4.5b). Excursion distance analysis also shows little change in the profile. The -1.0 metre contour retreated 85 metres landward between January and February and then moved 30 metres seaward between March and April, but by May had returned to almost the same position it had been in during March. Other than these instances, no other contours moved more than a few metres during the study period.

Looking at the longer term data in Figure 4.6, it can be seen that there were two periods of persistent erosion at this site. The first was between May and December 1990 and the second between January 1992 and July 1993. In both cases there have been subsequent, longer periods of recovery. This study period appears to have coincided with a period of recovery that began in July 1993, although it can be seen that throughout 1994 there were short periods of erosion superimposed on the generally accreting trend. The volume of sediment in the backshore declined markedly between January 1992 and July 1993 but has been building up slowly since then. The volume of sediment in the foreshore is also shown to be highly variable over a period of months and this can be seen where between July 1993 and January 1994 the foreshore volume doubled, from 118 m^3/m to 235 m^3/m, in a six month period.

Figure 4.5 Profile 2

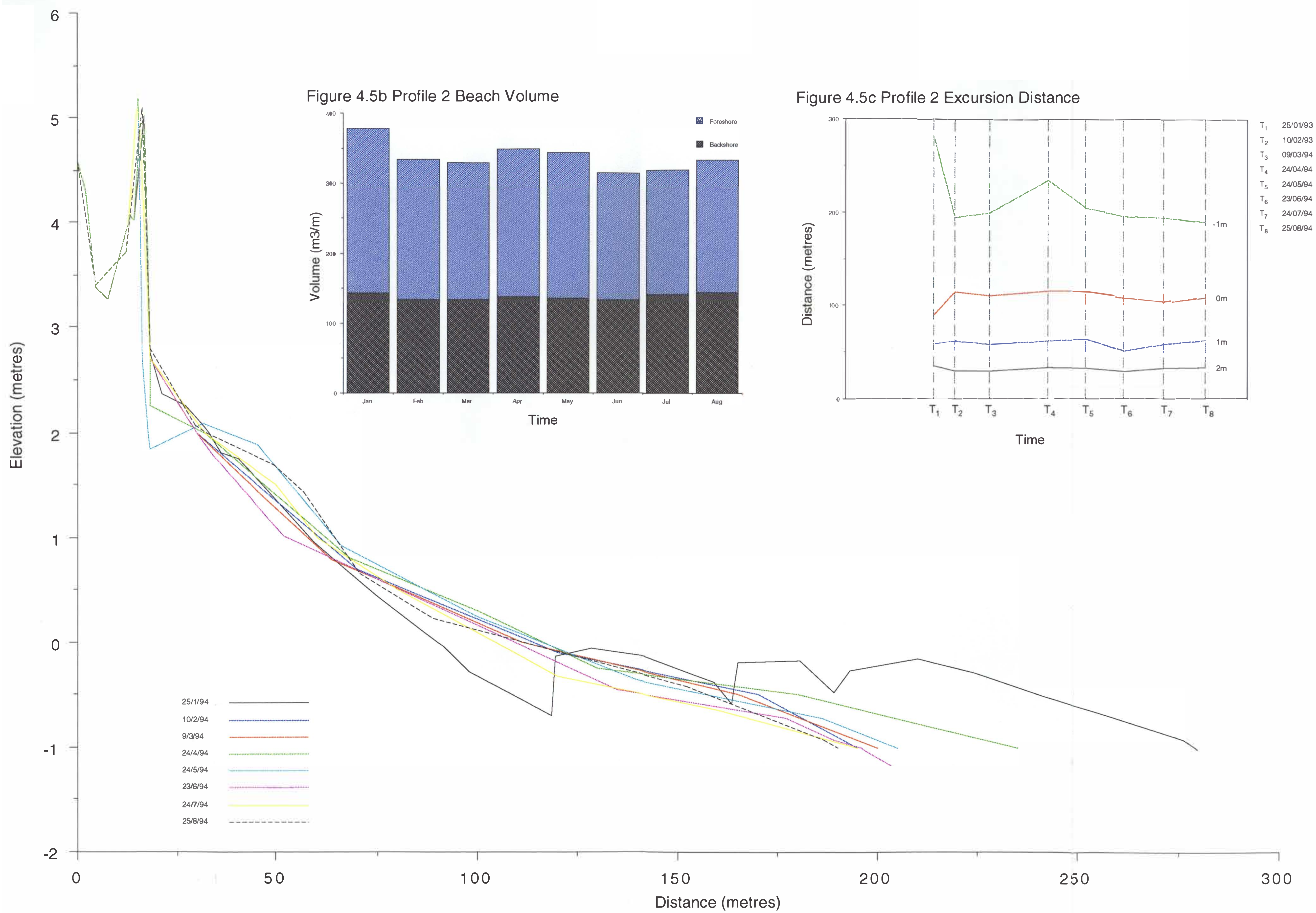


Figure 4.5a Profile 2 Plot

Figure 4.5b Profile 2 Beach Volume

Figure 4.5c Profile 2 Excursion Distance

Figure 4.6 Profile 2 1990 - 1994

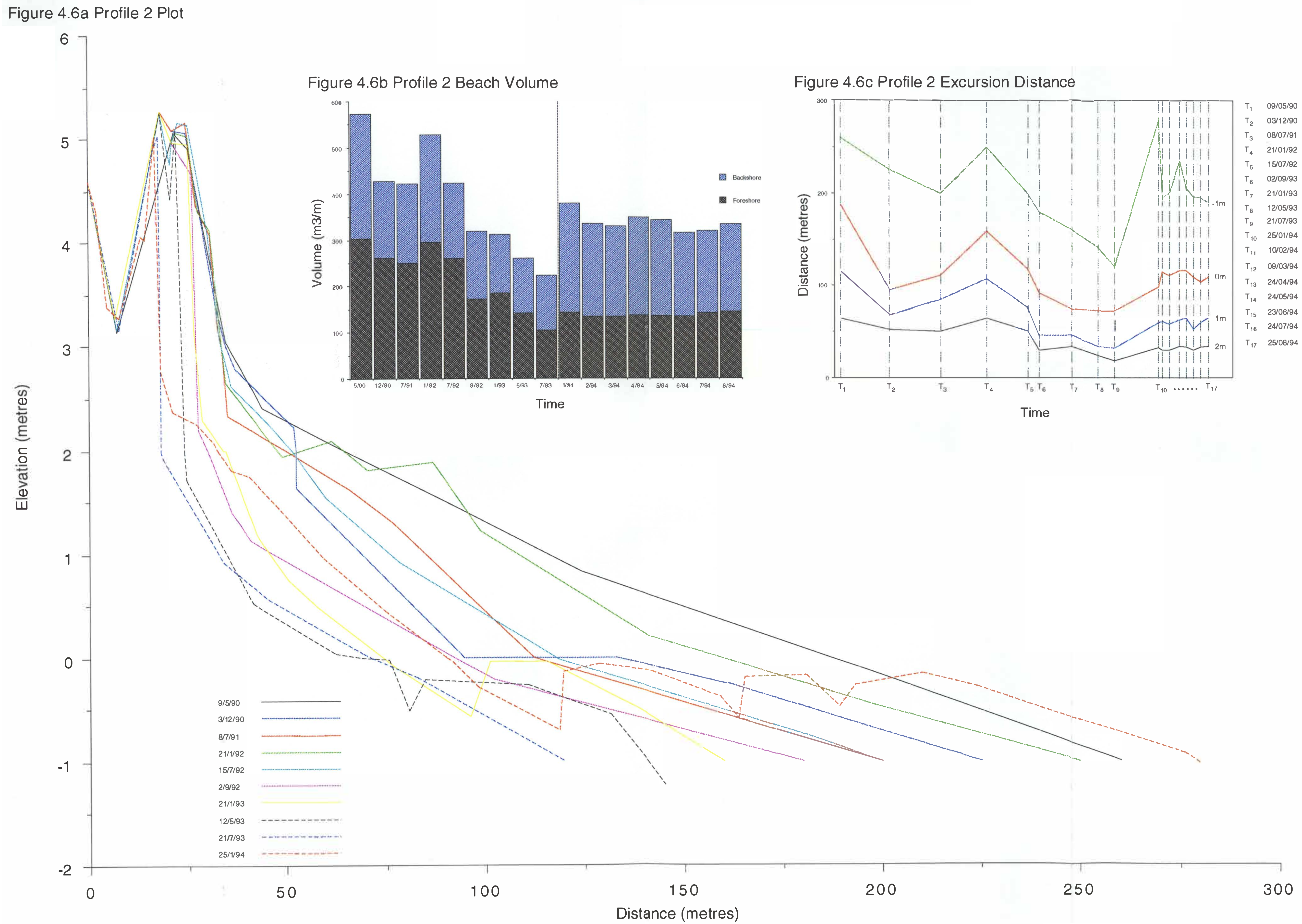


Figure 4.6a Profile 2 Plot

Figure 4.6b Profile 2 Beach Volume

Figure 4.6c Profile 2 Excursion Distance

4.4.3 Profile Three

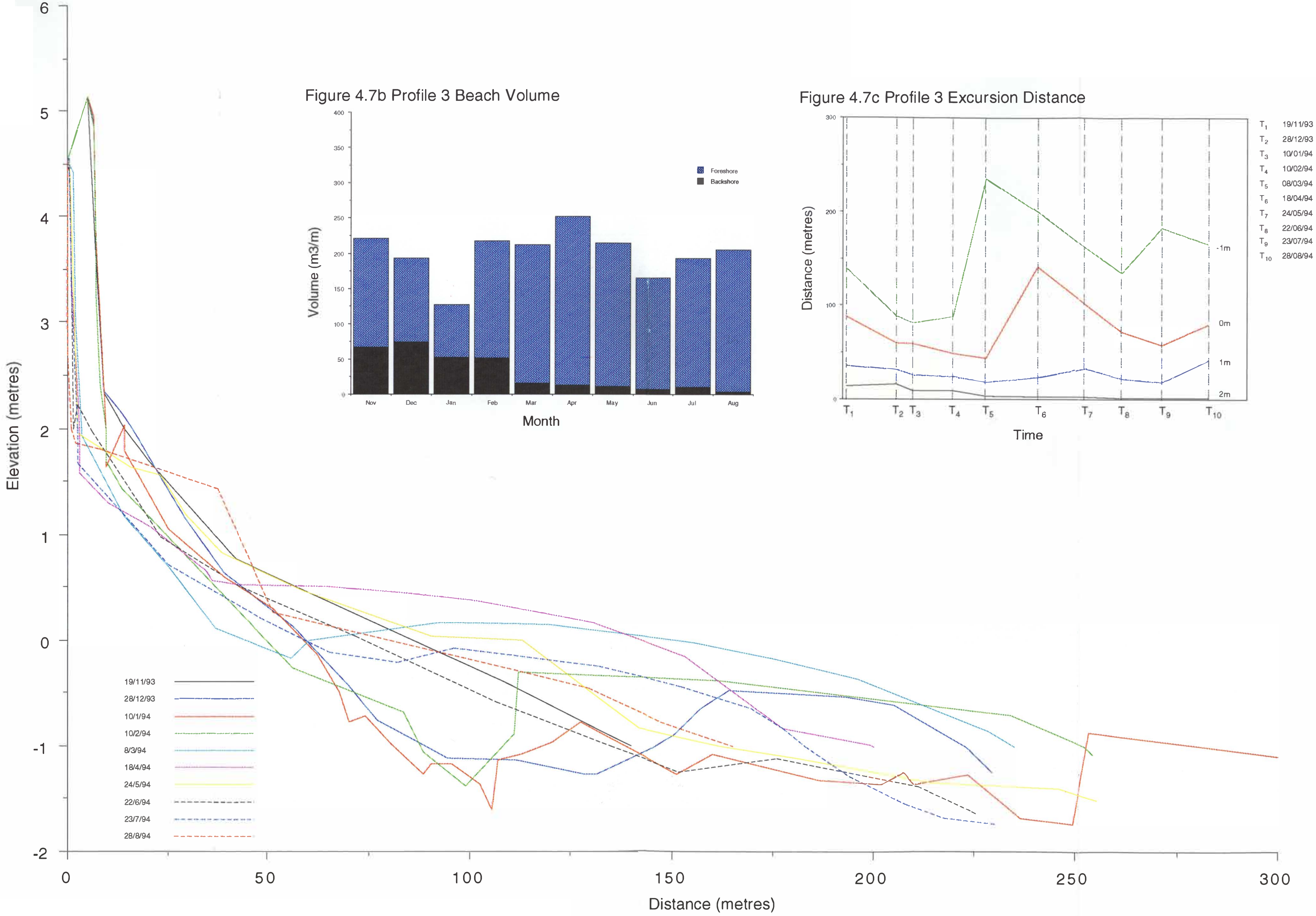
This profile was established in November 1993 with a peg 15 metres inland from a three metre scarp. There was no foredune at this site, although a backup peg was placed at the top of a inactive dune 30 metres further inland.

It can be seen from Figure 4.7a that this profile was highly variable throughout the study period. Between November and December 1993 the foreshore was significantly eroded although this is not particularly apparent when viewing the change in foreshore volume in Figure 4.7b. There was a 35 m^3/m decrease in volume although this was largely offset by the onshore migration of a large slug of sediment. Figure 4.7b shows a significant drop in volume between December and January and although the January profile (Figure 4.7a) shows the presence of a second slug of sediment, most of this lay below the -1.0 metre contour and therefore was not included in the volume calculation. By February this slug progressed 150 metres inshore and the foreshore volume doubled to 165 m^3/m. During March and April foreshore volume continued to increase as the slug of sediment welded itself to the beach. During the same period however, the backshore volume decreased as a result of the scarp at the back of the beach being cut back approximately 10 metres.

During May this profile began to take on a more concave shape and maintained this through to August. May and June also saw reductions in foreshore volume reflecting the redistribution of sediment as the profile took on a more equilibrium shape. This was also reflected in the retreat of the all the contours in Figure 4.7c. During July and August the foreshore accreted and the 0.0 and 1.0 metre contours advanced seaward. Throughout the entire study period the location of the contours and the total beach volume showed very little net change although the relative quantities in the foreshore and backshore had been altered markedly. In November 1993, 30 percent of the total volume was stored in the backshore but by August 1994 this had declined to only 1.8 percent.

Figure 4.7 Profile 3

Figure 4.7a Profile 3 Plot



4.4.4 Profile Four

Initially this profile ran southeast from a peg located in front of a five metre high pine tree 20 metres landward of a 2.5 metre foredune. However, in February when it became apparent that this site was being eroded the peg was moved inland a further 25 metres and placed at the top of a 5.5 metre inactive dune. Although this profile was only 200 metres south of Profile Three, it was observed that the foreshore was both significantly narrower and steeper than any of the three profiles to the north. This was interpreted as being a result of its closer proximity to the estuary's main outlet channel.

Of all the sites monitored Profile Four exhibited the most dramatic changes between November 1993 and August 1994. Between November and December a small amount of erosion is evident in the profile (Figure 4.8a), volume (Figure 4.8b), and excursion distance (Figure 4.8c) plots, but by January the beach had returned the same condition that it was in during November. Between January and February both the backshore and foreshore eroded, with the foredune being cut back leaving a small (0.7 metre) scarp, as shown in Figure 4.9. This is also reflected in Figure 4.8c which shows a landward retreat in all the contours.

Between February and March massive erosion occurred. The foredune was completely removed and the backshore was cut back exposing the roots of the pine tree which had previously been 20 metres behind the foredune (Figure 4.10). Total beach volume was reduced to only 65 percent of what it had been in February and 55 percent of what it had been in November. This erosion also exposed a number of metal drums, as shown in Figure 4.11. These were part of the groyne system installed in 1948 and had not been exposed on the beach face since they were buried by sand in the early 1950s. From examination of the excursion distance plot (Figure 4.8c) it would appear that the rate of change was not particularly rapid. This is however misleading because the plot represents the mean rate of change between survey intervals and in fact virtually all the erosion at this site occurred during a single week at the end of February and beginning of March.

Figure 4.9 February 1994: Erosion of foredune, Profile Four

Figure 4.10 March 1994: Removal of foredune, Profile Four

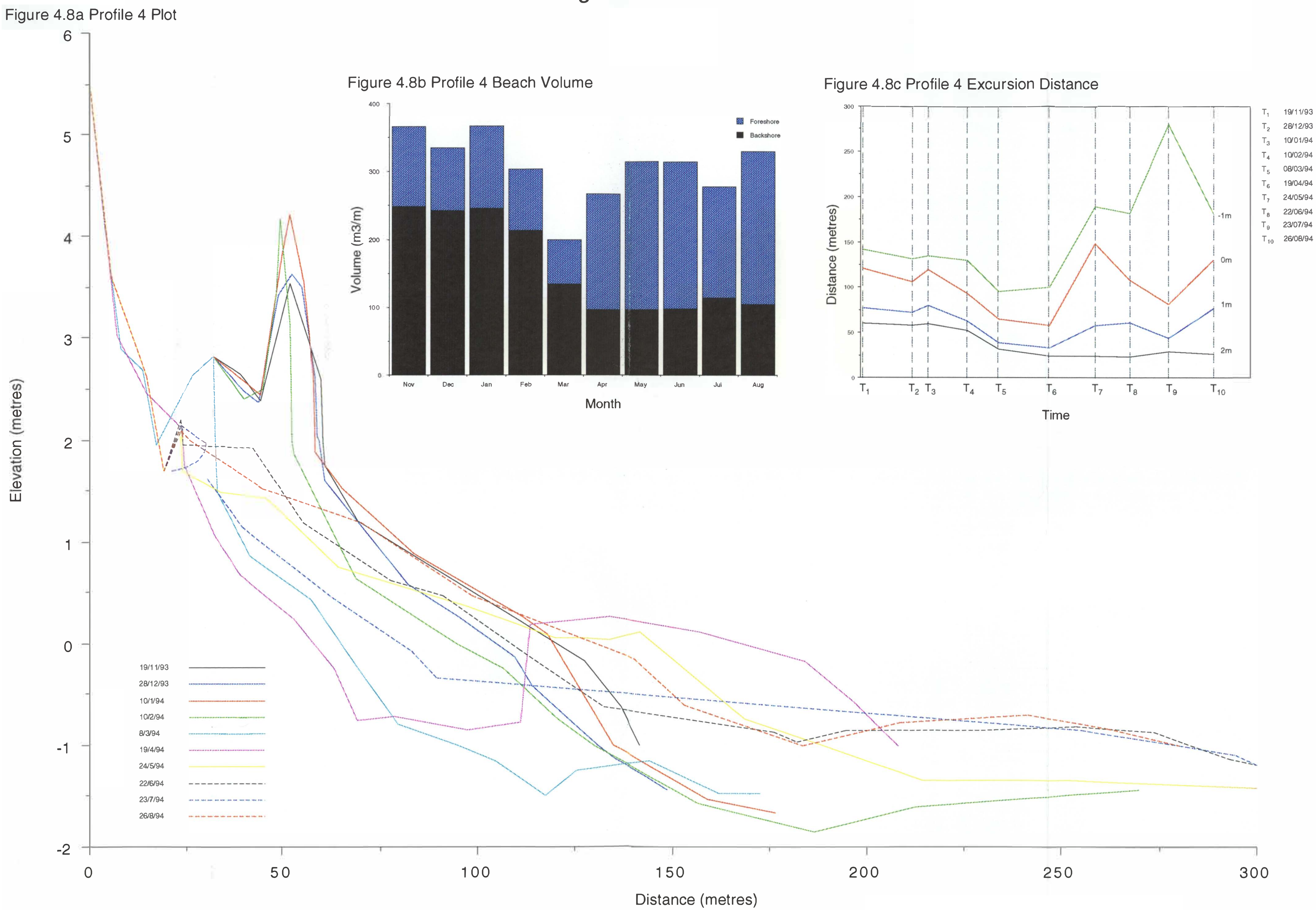
Figure 4.11 March 1994: Exposed drum groyne, Profile Four

Figure 4.12 May 1994: Accretion at Profile Four

While the April survey showed the backshore to be still eroding the foreshore accreted significantly (Figure 4.8a). Foreshore volume nearly tripled from 65 m^3/m to 170 m^3/m, with virtually of this increase being attributable to the large slug of sediment present between the 100 metre and 200 metre marks. From April onward the backshore stopped eroding and remained basically stable through to August (Figure 4.8b). The channel visible in the April plot had been filled in by May due to the onshore movement of a large slug of sediment. A berm formed on the backshore during May (Figure 4.12) and developed further during June, although by July it had been completely removed from the beachface. The foreshore continued to accrete until June and the profile also became considerably flatter, with a minimum gradient during the July survey of only 1:325 between the 100 metre and 250 metre marks.

Following some erosion of the foreshore during July, the August survey showed that the profile accreted again, although the -1.0 metre contour retreated 45 metres landward. The total beach volume in August 1994 was only 35 m^3/m less than what it was in November 1993 although the relative volumes in the foreshore and backshore had changed dramatically. In August 1994, 68 percent of the profile sediment was stored in the foreshore and only 32 percent on the backshore, whereas the corresponding percentages for November 1993 are almost the exact reversal of this.

Figure 4.8 Profile 4



4.4.5 Profile Five

Profile Five ran south of the distal end of the spit into the main outlet channel of the Avon-Heathcote estuary. The benchmark peg was located near the landward base of a 3.5 metre dune. In general this profile had a narrower and steeper foreshore than the other profiles which ran directly into the sea. The profile became very steep near the low water mark (typical gradients were in the vicinity of 1:10) which represented the northern bank of the main outlet channel.

Between November 1993 and February 1994 there was very little change in this profile. There was a small amount of accretion in the foreshore during January and early February (Figure 4.13b) and small movements (less than 10 metres) in the position of the channel edge (Figure 4.13a). Examination of the excursion plot (Figure 4.13c) however, shows that overall this profile showed an accreting trend between November and February.

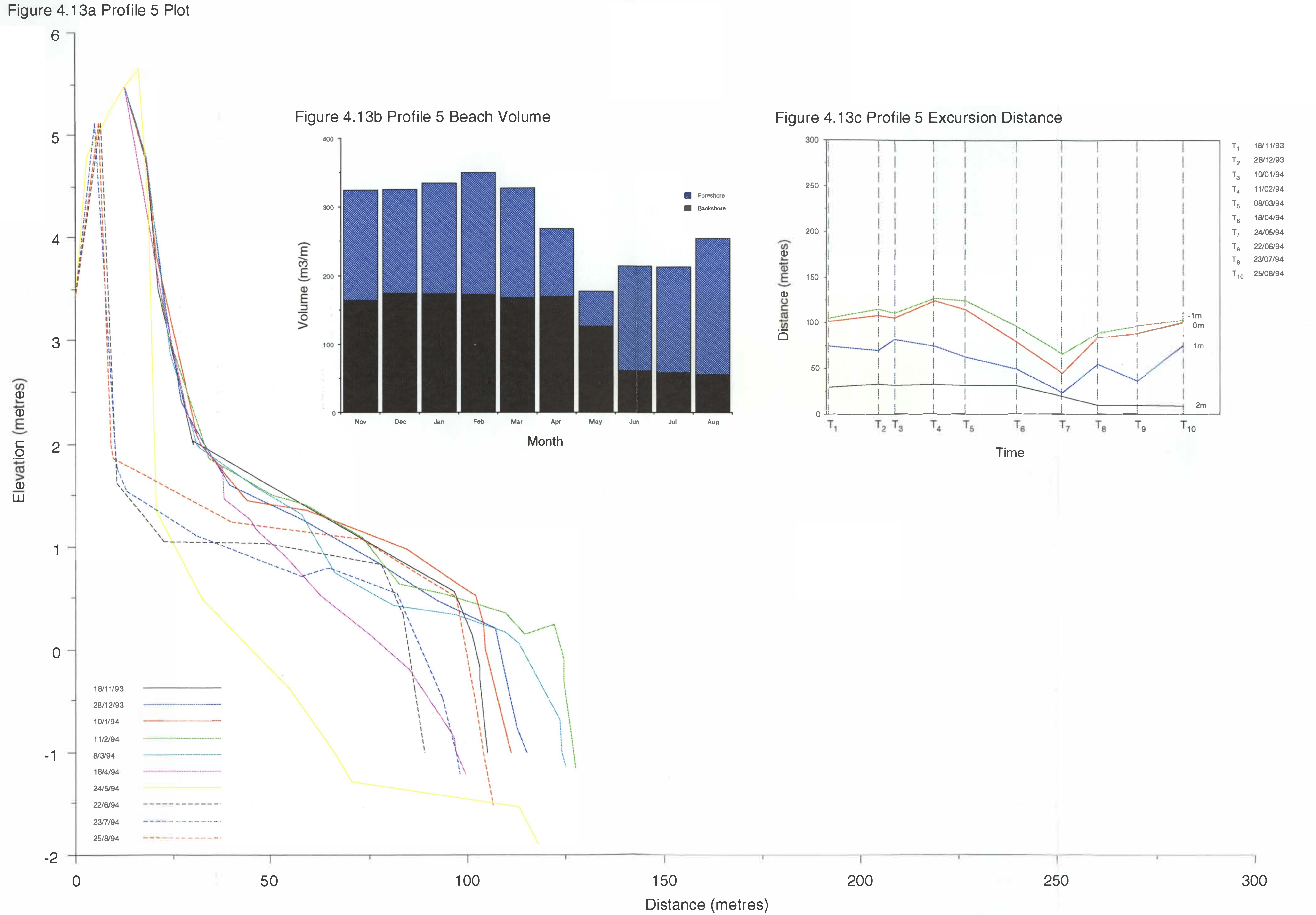
The March survey shows that the channel edge had shifted north by approximately two metres and the foreshore, between 60 metres and 110 metres had eroded slightly. This erosion continued and by mid April the main outlet channel had cut back 28 metres into the end of the spit and 60 m^3/m of sediment had been removed from the foreshore. In addition to this a small scarp had been cut into the base of the foredune. Between April and May this erosion accelerated with a further 40 m^3/m being removed from the foreshore, leaving the foreshore volume only 30 percent of what it had been in November 1993. It was also during this period that the backshore also began to show significant erosion with the base of the dune being cut back almost 20 metres leaving a four metre, almost vertical, scarp. Interestingly however, the main channel edge shifted 20 metres south during this period, although this is not shown on the excursion distance plot because it lies just below the -1.0 metre contour.

During June the foredune continued to erode with the base of the scarp retreating a further 10 metres reducing the backshore volume to just over a third of what it had been in November 1993. The foreshore however accreted markedly and in June contained three as much sediment as it had in May.

The period between the June and July surveys is noteworthy in that there were no net changes in the volumes of either the foreshore or backshore although there was some redistribution of sediment within the foreshore and the main channel edge moved south a few metres. The backshore also showed no change in the August profile although the foreshore accreted 45 m^3/m and the main channel shifted 12 metres further south.

From the volume (Figure 4.13b) and excursion distance plots (Figure 4.13c) it can be seen that change at this site between November 1993 and August 1994 can be divided into three distinct phases. The period from November to mid February was characterised by slow, yet steady accretion. From mid February to May there was comparatively rapid erosion and then this was followed by a second period of relatively slow accretion. These phases can be loosely linked to the north-south migration of the main channel edge the position of which is roughly approximated by the -1.0 metre contour in Figure 4.11c. In general during the accreting phases the channel edge moved south while during the period of erosion it moved north. It would however be presumptuous to assume a causal effect here as the movement of the channel edge were frequently quite small (less than 10 metres). It must also be remembered that these are net changes over approximately one month and it is likely that between surveys the channel edge moved in both directions.

Figure 4.13 Profile 5



4.4.6 Profile Six

This site is the first of two profiles which ran into the Avon-Heathcote estuary itself. The benchmark peg was located behind a 4.5 metre high dune, the base of which lay at approximately 0.5 metres above mean sea level. This is around 1.5 metres below the base of the dunes on the seaward facing profiles and reflects the fact that this site is not directly modified by marine processes. This means that the only waves acting on this profile were locally generated over short fetches and consequently were very small and had little, if any, swash runup. It also means that using the 2.0 metre contour as the interface between the nearshore and backshore is somewhat anomalous in this case because it places the start of the foreshore almost half way up the dune. In November 1993, the foreshore at this site was narrow (55 metres) and flat, with a gradient of only 1:430. At a distance of 80 metres the profile become significantly steeper with the gradient increasing to 1:15.

Figure 4.14a presents a rather confused picture of this profile. Frequently, much of the profile lay near or below mean sea level and it went up and down, often being dissected by one or more channels. A clearer impression of what occurred at this site is given by Figures 4.14b and 4.14c. The volume plot (Figure 4.14b) shows that the foreshore steadily accreted from 135 m^3/m in November 1993 to 240 m^3/m in May 1994, represented a mean rate of 15 m^3/m per month. Between May and July, 125 m^3/m of sediment was eroded but this was followed by slight accretion again during August. There was no change in the volume of the backshore at any time during the study period and the variations shown resulted from slightly different sampling points during individual surveys.

The excursion distance plot (Figure 4.14c) broadly shows the same trend as Figure 4.14b although two points should be noted. Firstly, following rapid accretion from 100 metres to 200 metres between November and March, the -1.0 metre contour then remained relatively static until June. The second point is that while the 0.0 metre contour retreated 85 metres between May and June the -1.0 metre contour did not begin to retreat until between the June and July surveys. Further to this, while the -1.0 metre contour continued to retreat the 0.0 metre contour began to advance into the estuary from June onwards.

There are two things of interest that the volume and excursion distance plots fail to show which are clearly shown in the profile plot (Figure 4.14a). The first of these are that while the foreshore was accreting the main outlet channel was being forced away from the benchmark and between February and March this movement was in the order of 100 metres. It would seem related to this that during March a second channel, about 50 metres wide and one metre deep, was scoured in the foreshore near the position occupied by the main channel in February. The second point is that from March onward the main channel generally then retreated back toward the benchmark so that by July it had returned to almost the same position that it had occupied in February. The second, minor channel rather than disappearing, persisted through until August and merely moved landward at a rate of approximately 10 metres per month.

Figure 4.14 Profile 6

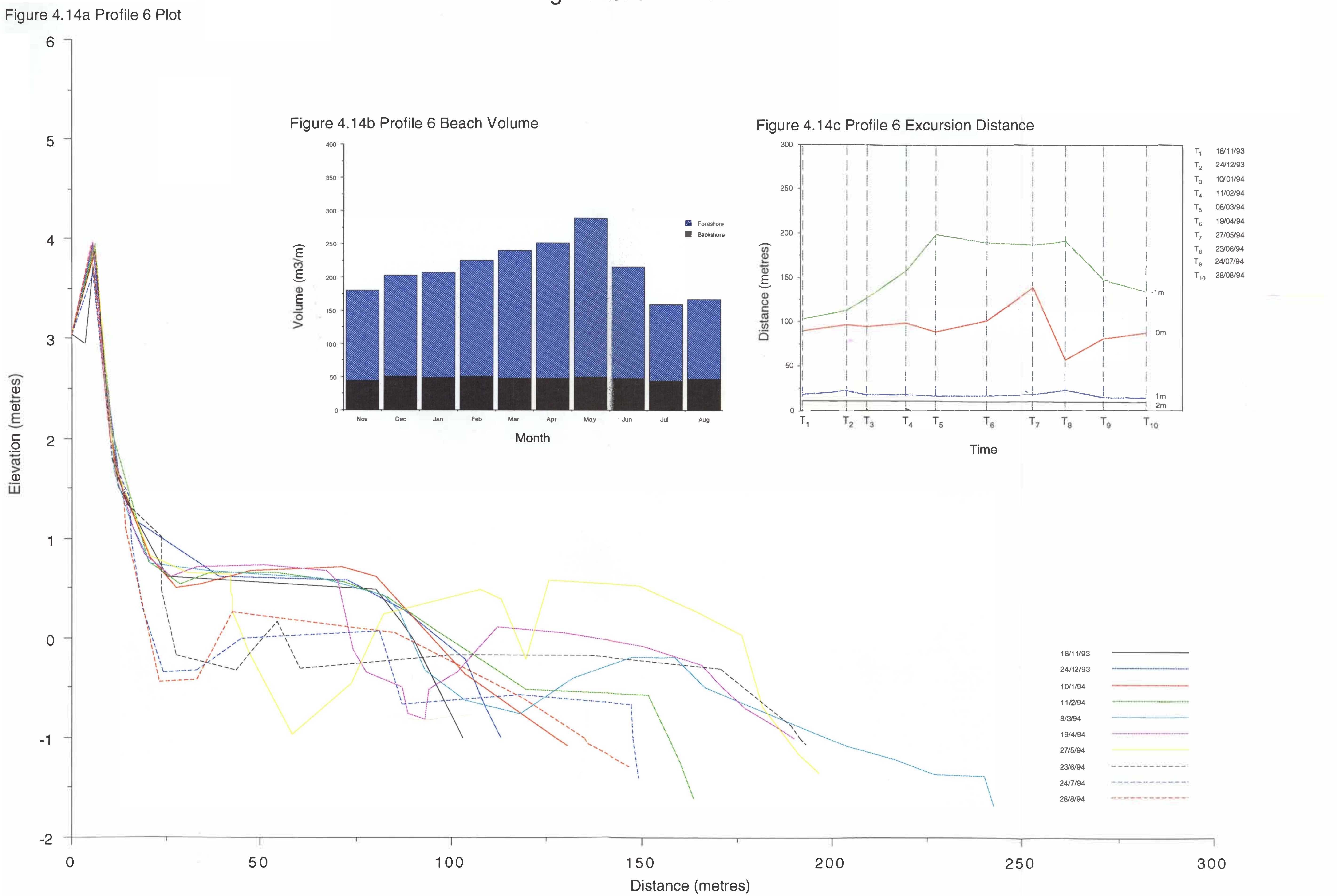


Figure 4.14a Profile 6 Plot

Figure 4.14b Profile 6 Beach Volume

Figure 4.14c Profile 6 Excursion Distance

4.4.7 Profile Seven

This is the second of the two profiles that ran directly into the estuary. The benchmark peg was located at the top of a well vegetated rise approximately four metres back from the foreshore. In November 1993 there was a very narrow (20 metres) and steep foreshore (1:15). The remainder of the profile consisted of intertidal sands which where only fully uncovered approximately 1.5 hours either side of low tide. This expansive intertidal area was separated from the rest of the beach by a 35 metre wide and 1.0-1.5 metre deep channel. Much of this profile lay between the 0.0 and -1.0 metre contours, although in any given survey there may have been several excursions above or below these points.

This profile was frequently marked with ripples, holes and channels making it difficult to accurately survey. When surveying subjective judgements were made regarding the breaks in slope to include, so that the plot that resulted gave a fair representation of the volume sediment in the profile. Consequently holes less than about five metres in diameter were ignored although where channels dissected the profile, these were surveyed regardless of their dimensions. Also because the profile fluctuated, crossing each contour multiple times, it was not particularly meaningful to include an excursion distance plot for this site.

The main reason for establishing a profile at this site was to gauge the quantity of sediment being transported and/or stored in the estuary, therefore the majority of this discussion will focus on the volume plot given in Figure 4.15b. The foreshore volume is shown to have been highly variable throughout the study period, with periods of both erosion and accretion. However, overall the profile displayed an accretional trend and particularly noteworthy is the sustained and substantial period of accretion (150 m^3/m) between January and April 1994. Between June and August however, 90 m^3/m was removed from the profile, indicating a reversal in the overall accretionary trend.

Although there was no real backshore at this site, the area above the 2.0 metre contour was included in Figure 4.15b to illustrate the effect of the landward migration of the channel nearest the spit. Throughout the study period this channel slowly moved toward the spit at a mean rate of around two metres per month, slowly consuming the narrow foreshore present during the November survey. By June the channel had reached the vegetated section of the profile and by August a 1.5 metre scarp had been cut into the backshore. The rate of movement also slowed down after June probably reflecting that the backshore was vegetated and therefore less susceptible to being eroded.

Figure 4.15 Profile 7

Figure 4.15a Profile 7 Plot

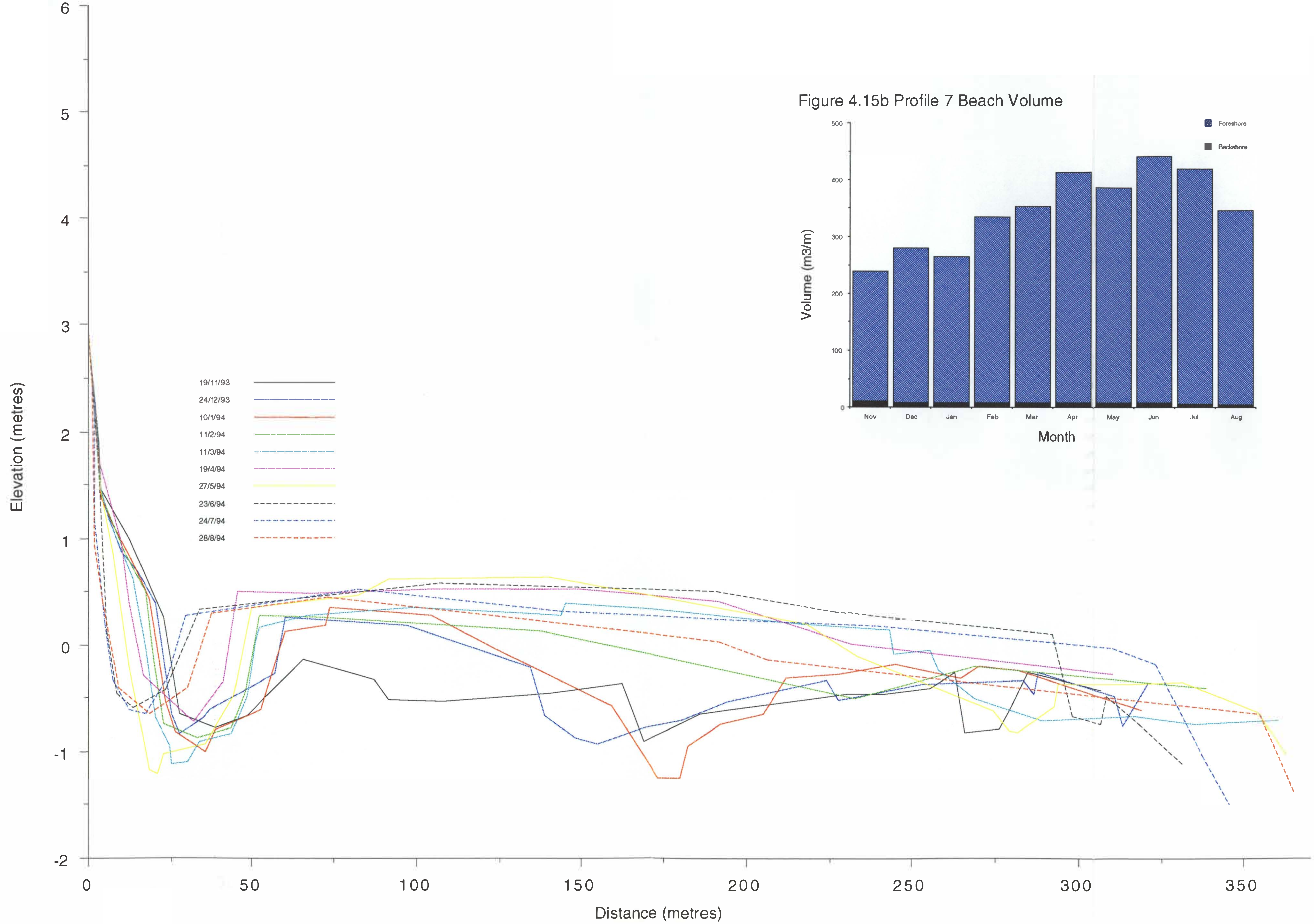


Figure 4.15b Profile 7 Beach Volume

4.4.8 Profile Eight

This profile was the first of three in Clifton Bay and ran 15 metres west of Shag Rock. It was established by the Canterbury Regional Council in May 1990. It was backed by a 3.5 metre high rock revetment, the base of which lies at approximately one metre above mean sea level. As a consequence of this there is no backshore at this site with the high tide mark being close to the base of the revetment for most of the monthly tidal cycle. The foreshore was steep (typically around 1:40) and narrow (approximately 25 metres) and steepened rapidly to 1:10 as it ran into the main outlet channel.

From Figure 4.16a it can be seen that there was little change in the back half foreshore throughout the study period with the exception of August when the beach directly in front of the revetment was lowered by approximately 0.75 metres. The major change in the seaward half of the profile was the incision of a 10 metre wide and 1.5 metre deep channel during April. This was maintained through until August in approximately the same place although the depth varied from month to month.

Much of the variability in beach volume shown in Figure 4.16b is largely a result of the movement in the position of the channel edge. Although these movements were small (maximum advance of 12 metres between February and March), proportionate to the rest of the profile this represented significant erosion or accretion of sediment. It is also interesting to note that there were no periods of sustained erosion or accretion at this site. The -1.0 metre contour in Figure 4.13c gives a good approximation of the channel position and this shows that in general the channel would move landward one month and then seaward again during every alternate month. From May onward the 1.0 metre contour almost perfectly mirrored the -1.0 metre contour so it can be seen that the beach become steeper and then comparatively flatter during alternate months.

The longer term data shown in Figure 4.17 shows similar trends as the data from this study. There were slight variations in the back half of the profile between 1990 and 1994 but the most significant changes were the onshore and offshore migration in the channel edge. However, as with the monthly 1994 data, these excursions all occurred within an envelope between 45 metres and 70 metres.

Figure 4.16 Profile 8

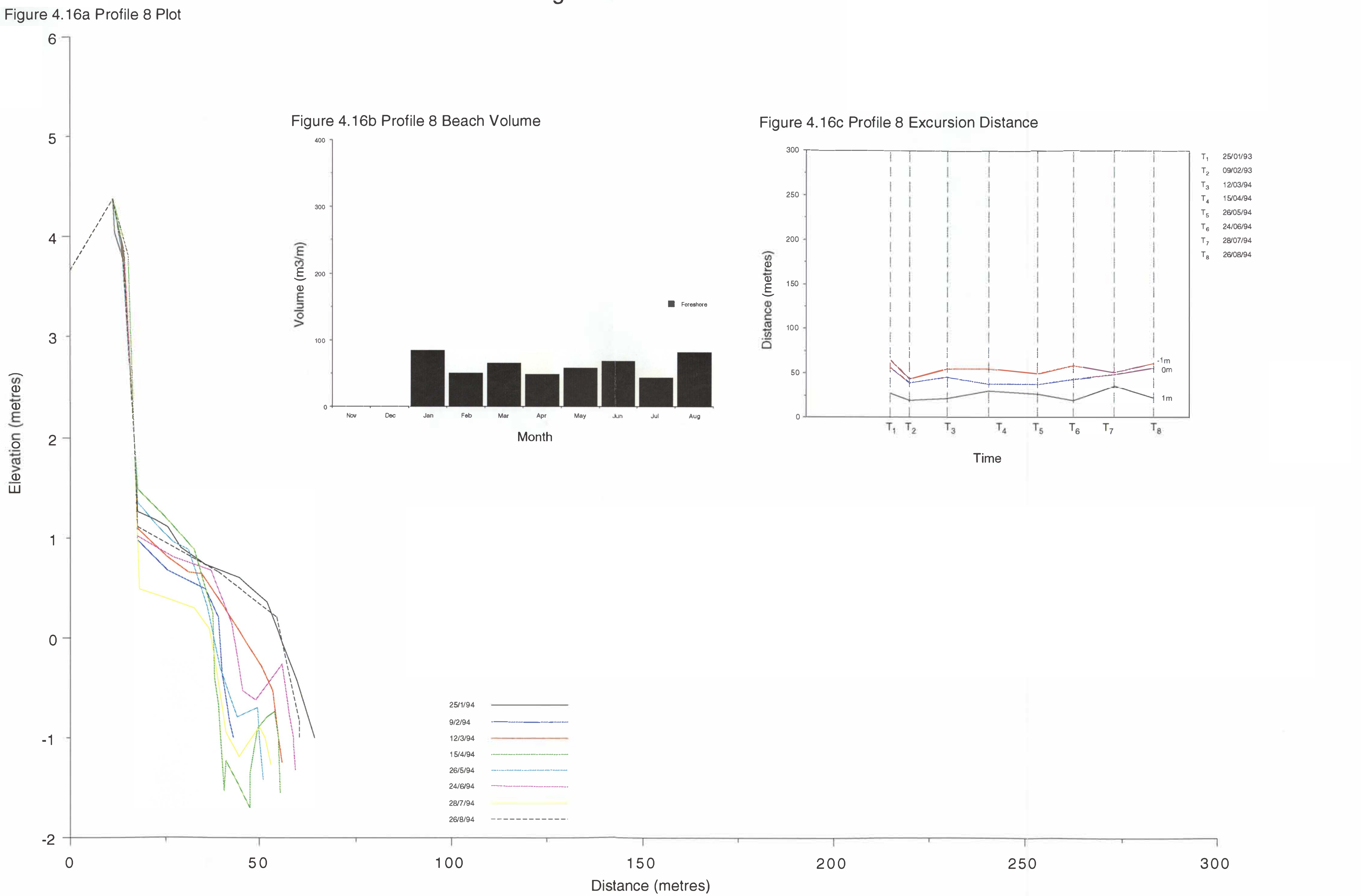
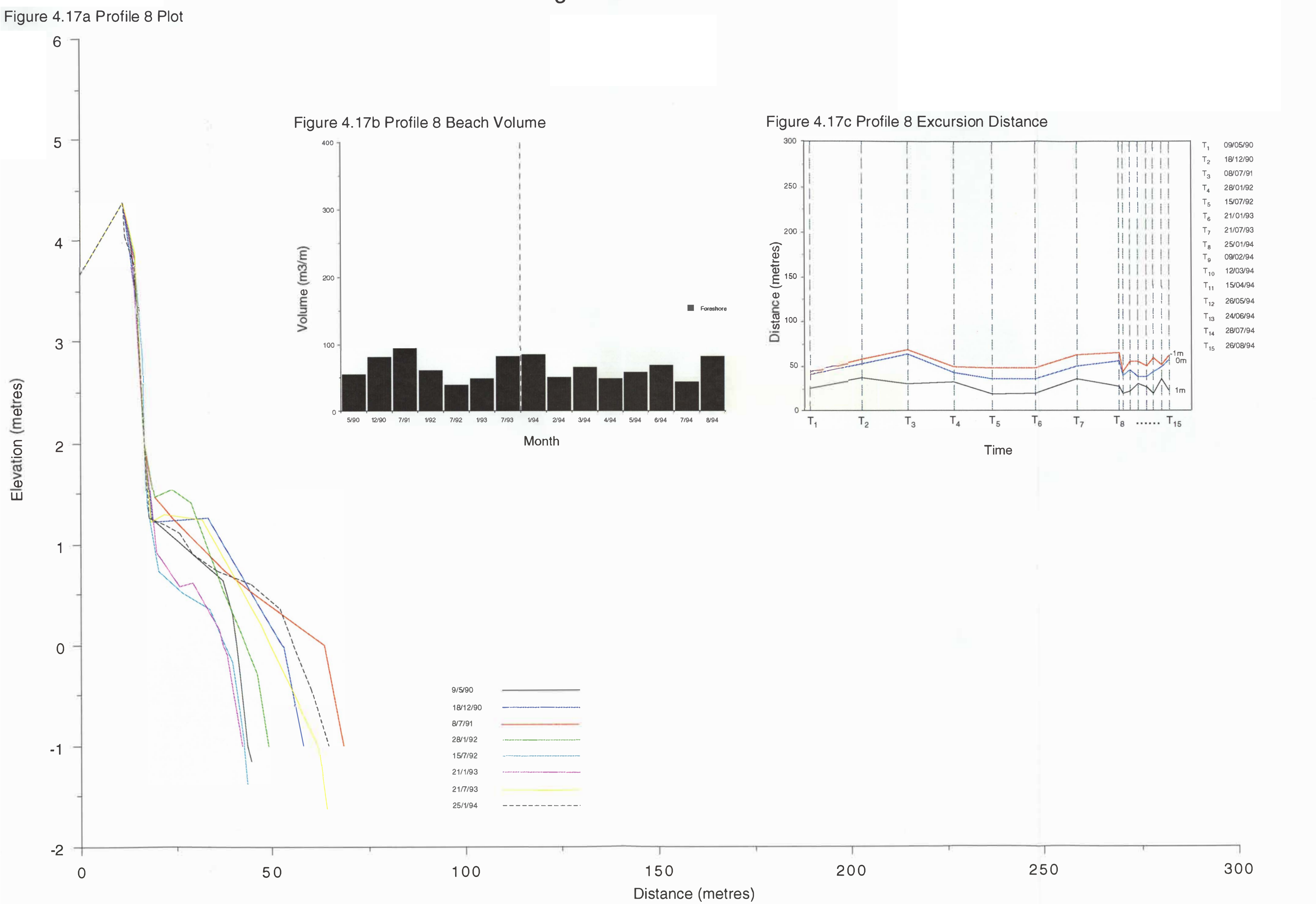


Figure 4.17 Profile 8 1990 - 1994



4.4.9 Profile Nine

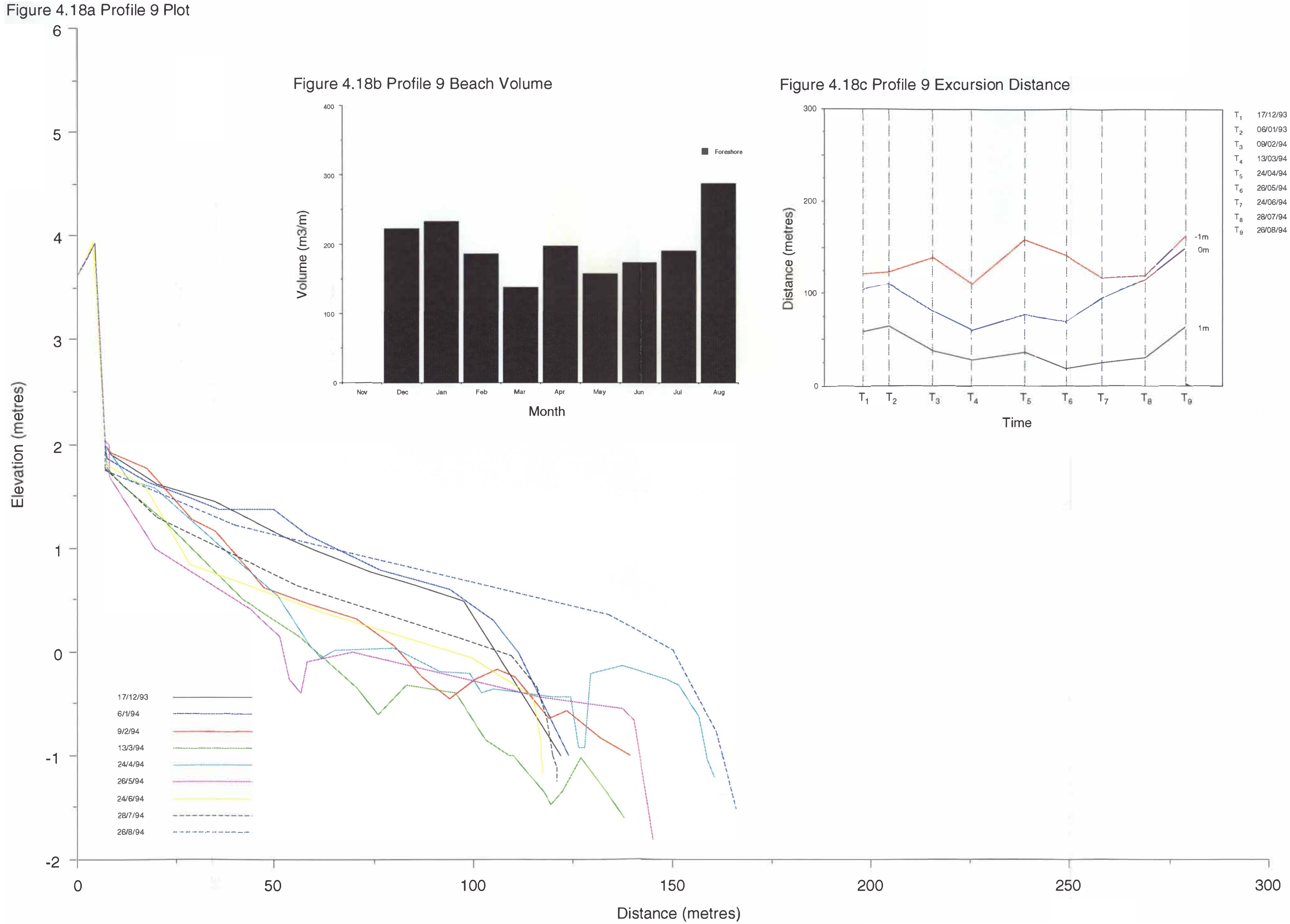
Profile Nine was established in December 1993 and runs into the main outlet channel approximately 25 metres east of Shag Rock. It is backed by the part of the same rock revetment which backs Profile Eight, although, while the top of the revetment is the same height (almost four metres above mean sea level), the base lies one metre higher at two metres above mean sea level. This also means that this site has no real backshore. The foreshore is comparatively wide (almost 100 metres in December 1993) and flat (typically around 1:60). Where the profile approached the edge of the main outlet channel the profile steepened markedly although the gradient varied considerably from month to month.

Between December and January there was little change in this profile other than the development of a small berm at 1.5 metres above mean sea level. During the period between the January and February surveys 50 m^3/m was eroded from the beach and the profile became less smooth. This rippled appearance persisted through until May and it can be seen in Figure 4.18a that in each of these months small channels had been scoured in the foreshore.

Despite some erosion between April and May, from March onward there was an accretionary trend at this site and this accelerated markedly between July and August when the main outlet channel shifted almost 50 metres offshore and the beach accreted nearly 100 m^3/m (Figure 4.18b).

Using the -1.0 metre contour in Figure 4.18c as an approximation of the main outlet channel location, it can be seen that the channel edge moved back and forth throughout the study period within a 50 metre envelope between 120 metres and 170 metres. It can also been seen that while the 0.0 metre and 1.0 metre contours followed parallel courses between December and April however, from April onward they began to diverge (i.e. the upper foreshore became flatter) while during the same period the -1.0 metre and 0.0 metre contours where converging (i.e. the lower foreshore became steeper).

Figure 4.18 Profile 9



4.4.10 Profile Ten

This was the most southern site monitored during this study and was first surveyed by the Canterbury Regional Council in May 1990. There were two bench mark pegs for this site which are located on the kerb at either side of the Esplanade. There was an accumulation of sediment in the backshore approximately one metre high and 40 metres in width, and resembles a small foredune. Between the 1.0 metre and 0.0 metre contours the profile had a moderate gradient however seaward of the zero metre contour the gradient diminished to around 1:80.

While the profile plots in figure 4.19a show that there was little variation in the backshore, the volume (Figure 4.19b) and excursion distance (Figure 4.19c) show that, despite erosion in February and June, the backshore showed an overall accreting trend.

Despite some accretion of the foreshore between January and February, Figure 4.19a shows a clear trend of erosion during the remainder of the study period. This erosion become accelerated in June with a small (0.4 metre) scarp being cut into the backshore near the 100 metre mark. Accelerated erosion continued through until August with the scarp steadily retreating landward and become enlarged, to 0.8 metres.

The excursion distance plot (Figure 4.19c) shows a steady landward retreat of the 1.0 metre and 0.0 metre contours throughout the study period. During June however, it can be seen that the -1.0 metre contour retreated 55 metres and eroded a further 30 metres back to the 130 metre mark during July and August. The magnitude of this erosion can be seen in Figure 4.19b which shows that the volume of sediment stored in the foreshore was reduced from 230 m^3/m in February to only 70 m^3/m in August. At least some of this sediment was taken and deposited just offshore and by June a shoal became visible (at low tide). This became progressively larger during July and August.

Figure 4.20 presents data gathered by the Canterbury Regional Council between May 1990 and January 1994 and some interesting comparisons can be made between these and the data from this study. In particular, attention is drawn to the massive erosion of the foreshore between the July 1992 and January 1993 which can be attributed to the severe southerly storms that hit Canterbury during August and September 1992. Referring back to Figure 4.19a, the position of the steep foreshore face on the August 1994 profile corresponds remarkably well with that on the January 1993 profile. Although following the 1992 storms the beach had four months of possible recovery before it was surveyed in January 1993, this similarity suggests that the erosion during this study period was of a similar magnitude, albeit at a slower rate.

The excursion distance plot in Figure 4.20c also elucidates an interesting trend in the -1.0 metre contour. The minimum distance of this contour in the Regional Council data was 210 metres in December 1990. While in January 1994 this contour was 10 metres seaward of this, by August 1994 it had retreated to a distance of only 138 metres, 72 metres landward of the December 1990 position. The 0.0 metre and 1.0 contours show a similar trend. In August 1994, they respectively lay two metres and 10 metres further landward from their previous minimum distance recorded during January 1993.

Figure 4.19 Profile 10

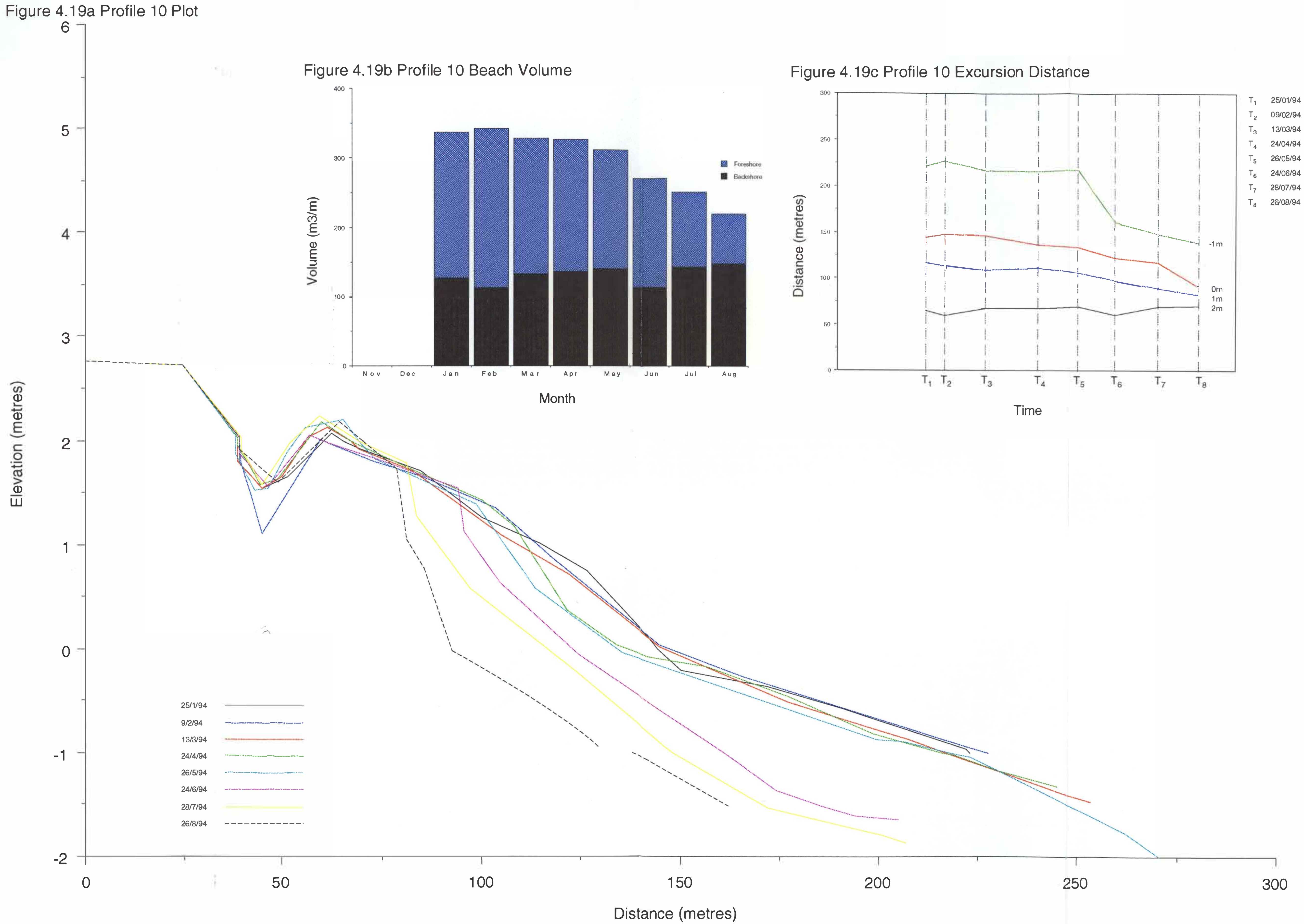
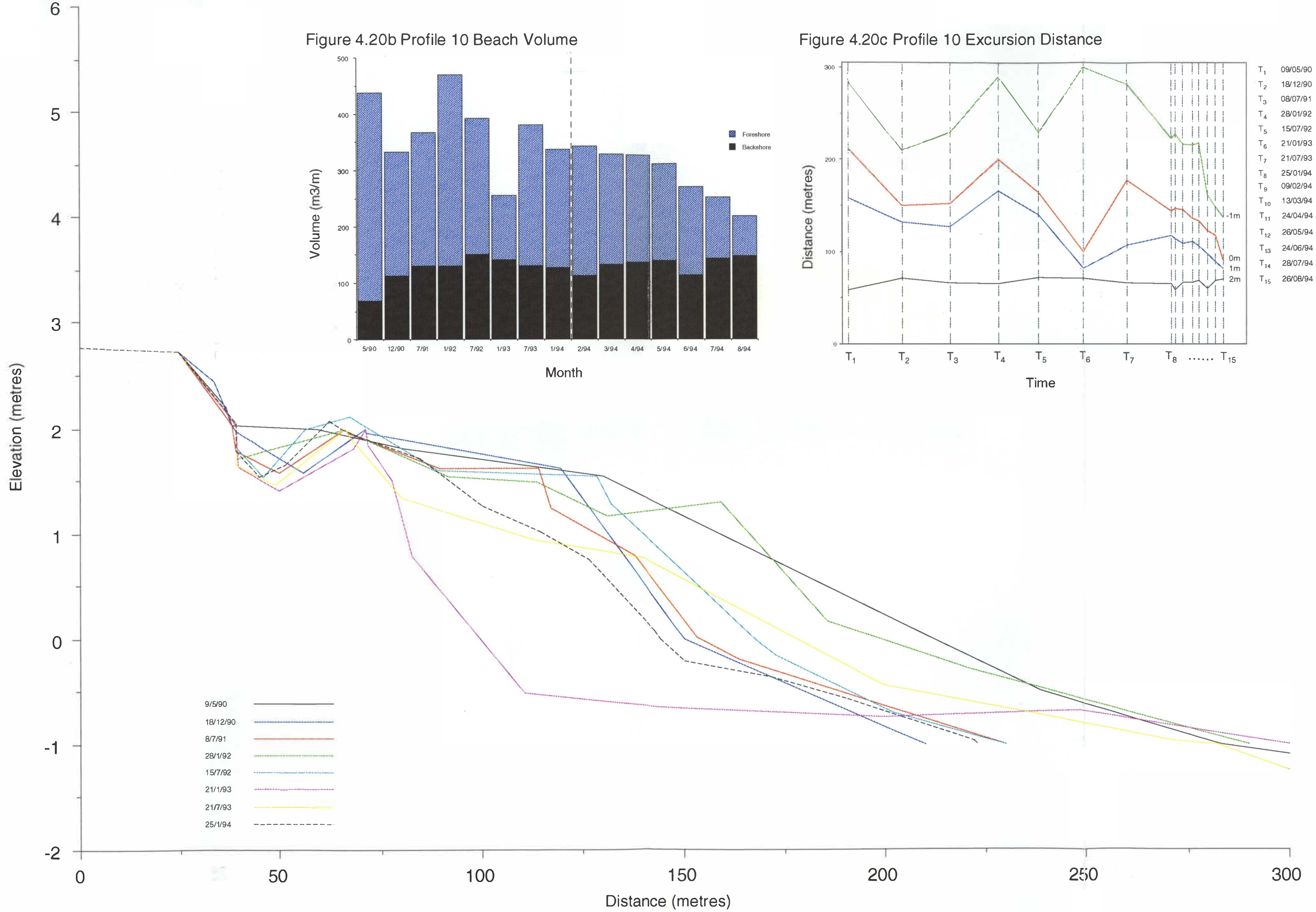


Figure 4.20 Profile 10 1990 - 1994

Figure 4.20a Profile 10 Plot



4.5 Discussion

The section above presents and discusses data generated from more 100 individual surveys taken at ten different sites over a ten month period. The broad trends are therefore somewhat obscured by the large amount of data presented so this discussion will begin with a very general summary of the changes that occurred before focusing down on comparisons between individual profile sites.

4.5.1 Overview of Beach Change

Figures 4.21, 4.22 and 4.23 are photographs looking east over the mouth of the Avon-Heathcote estuary and were taken on 18 December 1993, 28 April 1994, and 15 July 1994, respectively. Unfortunately they only provide a very limited view of the beach in Clifton Bay. All photographs were taken at approximately the same stage of the tidal cycle, that is, within 30 minutes of low tide.

As early as December 1994 (Figure 4.21) it can be seen that the tip of the spit had begun to erode (1). At the extreme left of the photograph the tip of the slug of sediment, identified on Profiles Three, Four and Five, is visible (2). Also note the sand island just inside the estuary (3) and the position of the small channel at the far left of the photograph (4).

Comparing the December photograph with the April one (Figure 4.22), it can be seen that major changes occurred. The foreshore on the seaward side of the spit tip was almost completely eroded and vegetation was removed (1) The southernmost extent of the spit tip moved from the seaward side of Shag Rock further into the estuary (2). The slug of sediment progressed over 100 metres down the spit but had not completely welded to the foreshore and a channel filled with water can just be made out (3). The section of the spit tip directly facing Shag Rock became considerably wider and was littered with a large amount of vegetation, mainly dead marram grass eroded from the seaward facing dunes (4). The sand island inside the estuary became enlarged and a large amount of sediment was now visible at low tide (5). The small channel shown in Figure 4.21 dissected this sand deposit and note also its proximity to the foredunes on the estuary side of the spit (6). One final thing to note in Figure 4.22 is the large slug of sediment in Clifton Bay which is also dissected by a channel (7).

Three months later, in July (Figure 4.23) the spit was quite different again. The slug of sediment had welded itself to the spit and the foreshore, in the vicinity of

Profile 4, became considerably wider (1). The southern facing section of the spit tip retreated markedly and the whole spit tip took on a more rounded appearance (2). The small channel which dissected the sediment deposit just inside the estuary still persisted and migrated closer in toward the spit (3). It is difficult to tell from the photographs whether the total volume of the deposit has declined, although the volume plots for both profile six and profile seven suggest that it did (4). The slug of sediment in Clifton Bay became significantly smaller (5) however although not shown in the photograph a very large sand island began to appear at low tide just to the right of the photograph.

In summary then it can be seen that between December and April a large amount of sediment was eroded from the seaward side of the spit but superimposed on this was the southward movement of a large slug of sediment causing quite considerable accretion. At least some of the sediment eroded from the spit was subsequently deposited inside the estuary. From the photographs it appears that some of this sediment also seems to have been deposited in Clifton Bay. This, however, presents somewhat of a paradox because the slug in Clifton Bay was moving in the opposite direction to the slug at South Brighton. By July the seaward face of the spit ceased being a source of sediment and the build up of sediment began to diminish both inside the estuary and in Clifton Bay.

Figure 4.21 Avon-Heathcote Estuary Mouth - December 1993

Figure 4.22 Avon-Heathcote Estuary Mouth - April 1994

Figure 4.23 Avon-Heathcote Estuary Mouth - July 1994

4.5.2 Movement of Sediment in the Vicinity of the Estuary Mouth

The large scale erosion and accretion discussed in this chapter occurred in a very localised area around the mouth of the Avon-Heathcote estuary. Profile One which was approximately 1 000 metres north of the main outlet channel showed very little change. Profile Two which was 500 metres north of the main outlet channel also showed comparatively little change. Only 100 metres south of this however, at profile three, there was severe erosion of both the backshore and foreshore and then later there was correspondingly large amounts of accretion. Likewise, Profile Four, only 220 metres from the main channel also experienced severe erosion followed by subsequent extensive accretion as also did Profile Five which ran directly into the outlet channel.

Both profiles inside the estuary experienced tremendous amounts of accretion although proportionately the profile closest to the outlet channel, Profile Six, accreted most.

In Clifton Bay, there was both erosion and accretion at profile eight although there were no obvious trends at this site. Profile Nine initially eroded and then accreted, with particularly strong accretion at the end of the study period. The southernmost profile, Profile Ten was 800 metres from the outlet channel but despite this consistently eroded throughout the study period and in the last two months erosion of the foreshore was comparable to the worst erosion at South Brighton, at Profiles Four and Five.

It would appear then that the events at South Brighton and Clifton Bay were quite distinct, although not necessarily mutually exclusive. At South Brighton the rate of change decreased with distance from the main outlet channel. In Clifton Bay however, the rate of change increased with distance from the main outlet channel.

From volume calculations of the profiles it is possible to track the movement of sediment that was eroded from each site. Erosion began at Profile Three in December and reached a peak in January and this is reflected by accretion in January of Profile Four. Profile Four began eroding in February with peak erosion in March. Some of this was deposited on Profile Five although this profile also began eroding in March reaching a peak during May. Profile Six accreted consistently between November and May and Profile Seven between November and April. At least some of the sediment eroded from the seaward face of the spit then, was rapidly transported south and deposited inside the estuary on the flood tide. After May when the seaward profiles had stopped eroding and were generally accreting the supply of sediment into the estuary was diminished and sediment was flushed out of the estuary on the ebb tide.

This sediment however does not seem to have been deposited on any of the profiles in Clifton Bay in any large quantities because during the peak erosion of Profile Four in March, profile Nine also eroded significantly and Profile Eight only showed a very small amount of accretion. There does however, seem to be a relationship between erosion at Profile Ten and accretion at Profile Nine and this was particularly strong following accelerated erosion from June onward.

It can be concluded therefore for both South Brighton and Clifton Bay that sediment eroded from the beach was transported toward the main outlet channel and, in the case of South Brighton, into the estuary itself. Direct exchanges of sediment between the two beaches however seems to have been prevented by the presence of the main outlet channel.

4.5.3 Magnitude of Change

It is difficult to determine the magnitude of the erosion around the mouth of the estuary due to the lack of long term data. While data from 1990 exists for three of the profiles, it is only at Profile One that there is a significant long term record. The utility of this however is diminished because, until the late 1980s, the site was only surveyed during periods of severe storm damage.

It is however possible to gain an idea about the magnitude of erosion from the events in the vicinity of Profile Four. The pine tree, directly on Profile Four, was one of six that were undermined and subsequently toppled. These were approximately 30 years old. The drums that were exposed were installed in 1948 and were completely buried within three to four years. There is no evidence that they have been exposed prior to their excavation in March 1994. These two lines of evidence suggest that the erosion in the vicinity of profile four was of at least a 40 year magnitude. Vegetation (marram grass and small shrubs) removed from Profiles Two and Five suggest that the magnitude of erosion at these sites was at least 10 years.

It is difficult to ascertain the scale of change at Clifton Bay, due to the absence of any backshore, although it does seem that the erosion at Profile Ten approached that associated with an extreme event.

4.6 Summary

Data gathered from ten profiles around the mouth of the estuary between November 1993 and August 1994, show that there were dramatic changes at least some of the sites. The magnitudes of change on the spit increased with proximity to the main outlet channel, with maximum erosion occurring at Profile Four and virtually no change at profile one. In Clifton Bay however, the magnitude of erosion decreased with proximity to the main outlet channel. Deposition of sediment inside the estuary decreased with distance from the channel. In all cases the erosion or accretion was rapid with large variations in beach profile between each monthly survey.

An attempt has been made to place the scale of erosion in some sort of long term context although this is impeded by the lack of data beyond 1990. It appears however that the erosion, at least near profile four, was of a scale not seen for at least 40 years.

Chapter Five: The Avon-Heathcote Ebb Tidal Delta

5.1 Introduction

The Avon-Heathcote ebb tidal delta is a large accumulation of sediment that lies seaward of the estuary mouth. Comparatively little data exists regarding the morphology of this delta, because its subaqueous nature makes it difficult to survey. The most recent information published regarding the delta's morphology is the 1976 hydrographic chart of Lyttelton Harbour (Hydrographic Office, Royal New Zealand Navy, 1976). Part of this chart is redrawn and shown in Figure 5.1. Although the number of soundings taken in the vicinity of the estuary mouth was relatively low, basic delta morphology can be seen. The 2.0 metre contour shows the delta margin to be crescentic in shape and immediately landward of this, water depth is comparatively shallow, with a number of shoals uncovered at low tide. Immediately seaward of the delta, water depth increases rapidly, with maximum gradients between the 2.0 metre and 5.0 metre contours of 1:40. Through the inlet gorge itself water depths of more than three metres are recorded, representing the main ebb channel. Seaward of the inlet gorge, the main ebb channel bifurcates, with shallower flood channels running northeast and southeast.

This chapter examines the morphological changes in the Avon-Heathcote ebb tidal delta between December 1993 and August 1994. However, because the delta is submerged, even at low tide, direct measurement was difficult. In cases such as this however, it is possible to gain considerable information regarding the subaqueous morphology through the analysis of wave breaking patterns. The analysis of photographs of waves to reveal underlying morphology has long been used by coastal geomorphologists (e.g. Lundahl, 1948; Tewinkel, 1963; Maresca and Seibel, 1976). All of these studies however rely on the analysis of images taken at a single point in time. This study exploits a comparatively new technique in coastal geomorphology using time exposure photography.

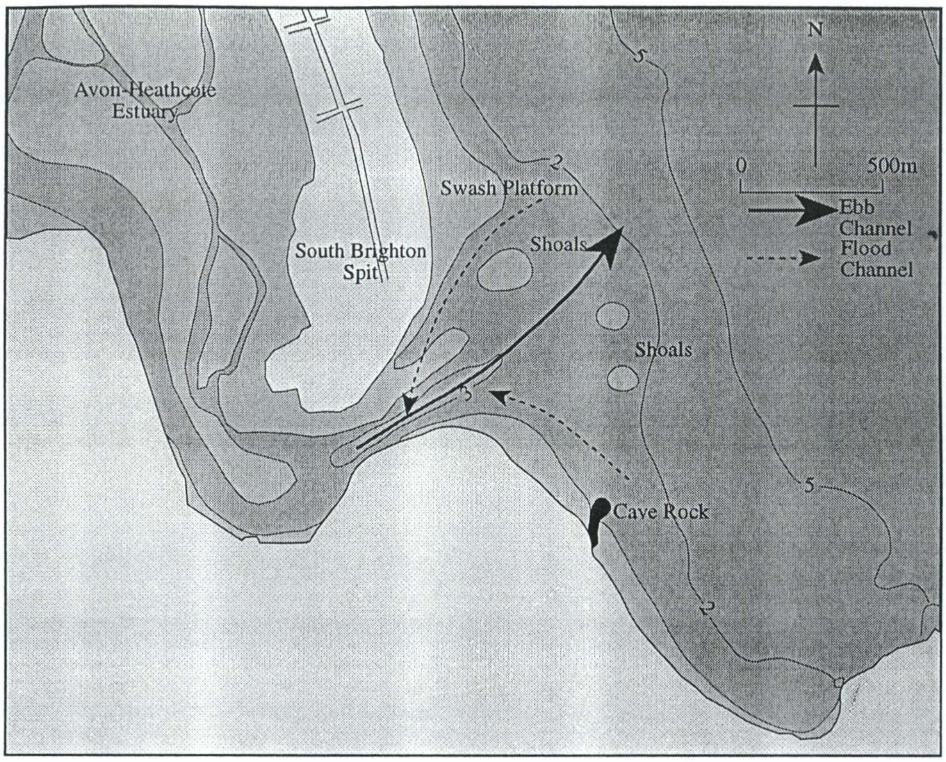


Figure 5.1 Morphology of the ebb tidal delta in 1976.
Arrows indicate inferred positions of the main ebb and flood channels.
Contours in metres below chart datum.
(redrawn from Sheet 6321 Lyttelton Harbour, Hydrographic Office,
Royal New Zealand Navy. 1976 edition)

5.2 Methods

5.2.1 Background

Because the Avon-Heathcote ebb tidal delta lies beneath the water surface even at low tide, it is difficult to gain direct data with regard to its morphology. It is however possible however to gain an idea about the shape of the delta using waves as a proxy indicator. This is based on two sets of fundamental principles in coastal geomorphology.

The first relates Snell's Law and the refraction of a shallow water wave when it encounters an area of variable depth, such as a crescentic shaped ebb tidal delta. In shallow water, wave velocity (C) is a function of water depth (d) and gravity (g):

$C = \sqrt{g.d}$ (CERC, 1977) (1)

This means that as a wave approaches the delta, the velocity of the part of the wave that is closest to the terminal lobe (i.e. in shallower water), will decrease relative to the rest of the wave. The remainder of the wave will be in relatively deeper water so will continue moving at a greater velocity. The rate of refraction is given by Snell's law:

$$\sin \alpha_2 = \left(\frac{C_2}{C_1} \right) \sin \alpha_1 \quad \text{(Snell's Law: CERC, 1977)} \quad (2)$$

where: a_1 is the angle a wave crest makes with the bottom contour over which it is passing

a_2 is a similar angle measured as the wave crest passes over the next contour

C_1 is the wave velocity at the depth of the first contour, and

C_2 is the wave velocity at the depth of the second contour

The result of this is that each wave approaching the mouth of the Avon-Heathcote estuary will be refracted in such a way to reveal a rough approximation of the morphology beneath the water surface. An example of this refraction is shown in Figure 5.2.

Figure 5.2 An example of waves refacting around the ebb tidal delta

The second principle on which this method is based is concerned with wave breaking in shallow water. Waves will break when one (or more) of three criteria are reached. The first of these concerns wave steepness, Stokes' wave theory, which predicts that waves will break when the crest angle is less than 120 degrees (e.g. Galvin, 1972). As waves enter shallow water, wave height (H) increases while wave length (L) decreases and consequently the wave becomes steeper. This makes the wave increasingly unstable and eventually the wave will break. The theoretical limit of steepness for a deep water wave was given by Michell (1893) as:

$$\frac{H}{L} = 0.142 \quad \text{(Michell, 1893)} \quad (3)$$

Critical wave steepness may also be achieved if the wave is being steepened by an opposing wind or current. The latter being particularly relevant in this study due to the strong ebb currents that flow through the main outlet channel.

Secondly, as waves move shoreward and wave height increases, the velocity and diameter of individual water particle orbits will also increase. As mentioned above however, when a wave enters shallow water its velocity decreases. This means that eventually the individual water particles reach a critical point and break through the wave form (Galvin: 1972). Also, as waves enter shallow water, they begin to act independently rather than as a wave train and because the wave crest and wave troughs are in different water depths they will travel at different velocities. The wave crest velocity is given by:

$$C = \sqrt{g(d+H)} \quad \text{(Daily and Stephan, 1953)} \quad (4)$$

While the trough will only be travelling at:

$$C = \sqrt{g(d-H)} \quad \text{(Daily and Stephan, 1953)} \quad (5)$$

Consequently the wave will become asymmetrical with the front face steeping up and the back slope becoming flatter. This leads to instability and the wave will break. The ratio between wave height and water depth is therefore important for determining breaking. As a rough guide, the critical value for this ratio is frequently given as 0.78, although it has been found that this vary greatly depending on other factors, such as bottom roughness and slope (Galvin, 1969; CERC, 1977).

In addition to this, at any given time it is likely that there will be a sea state with waves of variable height. Because breaking is determined by the ratio between wave height and water depth, it follows that at any given time the pattern of wave breaking will appear somewhat irregular. Larger waves will break further offshore while smaller waves will progress further inshore before breaking. This introduces an uncertainty as to what a lack of wave breaking means. It is possible that areas of no breaking represent deep water or it may merely be a reflection of lower wave height. Time exposure photography removes much of this statistical uncertainty by averaging any modulations in wave height over a longer period (Lippmann and Holman, 1989).

Time exposure photography, in a coastal environment, was first used by Holman and Lippmann (1987) as a means to quantify sand bar morphology in Duck, North Carolina. Photographs were taken from a 14 metre tower located on the dune crest using a standard 35 millimetre camera. Exposure time was set at 10 minutes and, to prevent overexposure, was fitted with either an 11 or a 14 neutral density filter, depending on lighting conditions. This technique has since been used in a New Zealand setting by Bailey and Shand (1993). Their study of offshore bars in Wanganui used similar equipment to Holman and Lippmann (1987), although photographs were taken from a site 100 metres behind and 43 metres above the spring high tide mark on the beach.

This study differs from Holman and Lippmann (1987) and Bailey and Shand (1993) in a number of ways so the following will give a detailed description of techniques used in this study.

5.2.2 Photographic Site

Holman and Lippmann (1987) taking photographs from a temporary tower and Bailey and Shand (1993) taking photographs from a marine cliff had an advantage over this study in that they were relatively close to the subject that they were photographing. Photographs in this study however were taken over considerably larger distances and sites were chosen on the basis of three criteria. The most important was an unobstructed view of the ebb tidal delta. Due to the nature of the landscape this proved to be surprisingly difficult and the majority of accessible sites could not be used due to the presence of houses, trees, or hills in the line of photography. The second criterion was based on distance from the delta because accuracy of the rectified image would decrease with distance (Holman and Lippmann, 1987). Finally height was important because if photographs were too oblique then it became increasingly difficult to discern wave breaking patterns.

In the end, only one suitable site was found and this was located on the Summit Road approximately 3 000 metres southwest and 210 metres above the mouth of the Avon-Heathcote estuary. Its location can be seen in Figure 5.3.

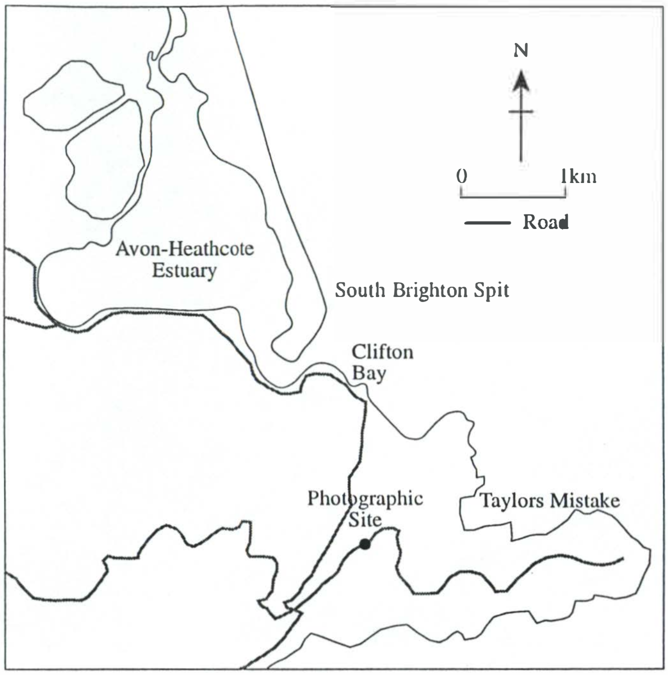


Figure 5.3 Location of the photographic site

5.2.3 Equipment

i) Camera

A *Pentax K1000* camera was used in conjunction with a *Pentax A-zoom* (28-80 millimetre) lens. Initially a *Takumar-A* two times tele-converter was also used to increase the maximum focal length to 160 millimetres. It was found however that it was difficult to rectify images when focal length was this long, due to draughting restrictions so the tele-converter was not used. The camera was mounted on a tripod and activated using a standard cable release.

ii) Filters

The camera was fitted with three different types of filters. The first was an ultra-violet filter. While ultra-violet light is not visible to the naked high, it can have a profound effect on photographic results due to the sensitivity of silver halides to light with short wavelengths (Davis, 1972). In addition to this, light becomes scattered over long distances and this scattering increases with lower wavelengths (Horder, 1958). The ultra-violet filter therefore also served to reduce haze.

The camera was also fitted with a polarising filter. When light is reflected from a smooth surface, such as water, it becomes polarised. A polarising filter prevents this light entering the lens and thereby eliminates glare while increasing contrast.

Because the time exposures were taken during daylight the amount of light entering the lens had to be controlled using neutral density filters. The intensity of these filters are measured in stops, with each stop representing a 50 percent reduction in light. The 11 and 14 stop neutral density filters used by Holman and Lippmann (1987) and Bailey and Shand (1993) were expensive and unavailable in New Zealand. So, instead this study employed two, two stop neutral density filters. One was mounted on the front of the lens while the other was fixed to the back element of the lens. Because incoming light had been filtered by the front filter before passing through the aperture to reach the second filter, the effect was to increase the effective number of stops from four to the equivalent of an eight stop neutral density filter (C. Pennington, Department of Geography, University of Canterbury, *pers. comm.*).

In addition to the above filters, trials were also made with a red filter to see if this would increase the contrast between the sea and the breaking waves. The improvement was negligible under all lighting conditions except in poor light where contrast deteriorated further. The reason for this is unknown but is probably linked to the length of the exposure time.

iii) Film

Photographs were taken using film of variable speeds and quality. Quality was tested first, and it was found that exposing lower quality film, such as *Kodak Gold*, for long periods of time gave poor results. Film speed, the rate at which the film absorbs light, was found to be unimportant. It was expected that faster film would become overexposed while slower film would be underexposed. Trials however, using *Agfa Ultra* (50 ISO) and *Agfa Optima* (200 ISO) film, yielded similar results. This was interpreted as rather than compounding the differences, the length of exposure and the use of neutral density filters reduced the effect of variations in film speed. Most photographs taken during this study used *Agfa Optima* (200 ISO) film and were processed in colour.

iv) Procedures

The optimal length of exposure was determined by varying the shutter speed from one minute to 20 minutes at one minute increments up to five minutes and thereafter at two minute increments. This was done using the same film (*Agfa Optima*) and the procedure was repeated over a number of days. At speeds of less than four minutes it was found that the full benefits of time exposure were not achieved and fine detail such as channel edges were not as sharp. Six to 12 minute exposures consistently gave the best results with speeds slower than this resulted in slight, but increasing, overexposure. Analysis of early photographs showed that an eight minute exposure gave consistently sharper definition than any other, so this was the speed used throughout the study period.

The photographic effect (E) is dependent on the exposure time (t) and illumination (I) of the film. This is known as the Law of Reciprocity and is given by:

$E=I.t$ (Horder: 1958) (6)

Throughout this study, exposure time was held constant at eight minutes, so the only way to manipulate the photographic effect was by varying the degree of illumination. This is achieved by altering the aperture setting on the camera, with each successive setting halving the amount of light reaching the film. Generally it is possible to calculate the correct aperture setting for a given shutter speed using an exposure metre. In the case of a long time exposure however, this law begins to fail (Holman and Lippmann, 1987) and it becomes difficult to systematically determine the appropriate aperture setting for given lighting conditions. By varying the aperture setting between f11, f16 and f22 under different lighting conditions, as measured by a *Jonan* selenium exposure metre, is was however possible to develop a rough guide. In general, where the intensity of light had an exposure value (EV) less than 15 , f16 gave the best results, while above 15 (EV) the aperture was decreased to f22. Under all lighting conditions an aperture setting of f11 overexposed the film to an extent that it could not be printed.

An additional problem encountered was the breakdown of contrast in poor lighting conditions. This was generally a result of cloud and where light was less than about 13 (EV), it became almost impossible to distinguish the breaking waves from the surrounding sea. An attempt was made to overcome this by altering the aperture setting, film speed, and number and type of filters. These variations resulted in either no appreciable change or gross overexposure of the film.

Time of photography was also an important consideration. This method relies on the presence of breaking waves and, in general, because the number of breakers decreases with water depth, the best time to take photographs, for this study, was around low tide. Breaking, however can also been induced by an opposing current so maximum breaking occurred immediately prior to low tide on the ebb flow.

Although wave breaking was important, there were also a number of other significant environmental considerations. Firstly, and obviously, photographs had to be taken during daylight but there also needed to be enough light to provide contrast between the waves and surrounded sea. Cloud cover was important, not only because it largely determined contrast, but also because if there was to much low cloud the horizon was obscured and the location of the horizon was required in order to rectify the photograph. Where the sunlight was not filtered through clouds, the time of day became an important consideration. In the morning when the sun was lower in the sky, glare from the water made photography difficult, despite the use of an ultra-violet filter and this was particularly a problem in the winter months. Because photographs were taken looking northeast over the delta, best results were achieved in the afternoon when the sun was high in the sky, or later in the afternoon when the sun was out of the photographic line.

v) Evaluation

Table 5.1 details the days on which time exposure photographs were taken. For each day the result is given as good, fair, poor, or none. This section is primarily concerned with days when no result was achieved, the photographs that were rated good, fair or poor, form the basis of the next section and will be discussed in detail there. In Table 5.1, no result relates to whether or not the photograph could be used. It does not refer to whether or not a print could be made from the negative. From Table 5.1 it can be seen that photographs were taken on 27 separate days between December 1993 and August 1994 and of these only 10 could be used in this study.

It can be seen that technical problems were the main reason for no result being achieved. Particularly unfortunate were the five days work between 12 March and 12 April that were destroyed at the photo lab. The other two problems experienced were insufficient breaking and lack of contrast due to cloud. Table 5.1 only shows the days on which photography was attempted, it does not show the numerous days on which, despite travelling to the study site, no attempt was made to take photographs. While no record was kept, there was approximately 20 additional days when no photography was even attempted due to absolutely no breaking, excessive cloud cover, or too much glare from the water.

Date	Result	Explaination
18/12/93	None	No waves breaking on delta
27/12/93	Good	
06/01/94	Good	
07/01/94	None	No waves breaking on delta
20/01/94	None	Film overexposed (camera accidently opened)
21/01/94	None	Film overexposed (camera accidently opened)
25/01/94	None	No waves breaking on delta
08/02/94	None	No waves breaking on delta
19/02/94	None	7/8 cloud, insufficient contrast
20/02/94	Poor	
12/03/94	None	Film destroyed at photo lab
13/03/94	None	Film destroyed at photo lab
21/03/94	None	Film destroyed at photo lab
30/03/94	None	Film destroyed at photo lab
12/04/94	None	Film destroyed at photo lab
13/04/94	Good	
18/04/94	None	Few waves breaking, excessive haze
28/04/94	Fair	
02/05/94	None	Film overexposed (incorrect apperture setting?)
15/05/94	Fair	
21/05/94	None	Cable release broke
14/06/94	Poor	
26/06/94	None	Delta obscured by low cloud
10/07/94	None	Excessive glare
11/07/94	Poor	
29/07/94	Fair	
26/08/94	Fair	

Table 5.1 Photographic Results

Up until April the main problems were technical failures and therefore not a reflection on the technique itself. From May onward it became increasingly difficult to get good photographs. Because the sun was lower in the sky, on clear days there was too much glare in the mornings to get good results and so photographs could only be taken between about 1300 hours and 1630 hours (when the sun began to set). Even then it was desirable for the sunlight to be filtered through some cloud, although if there was too much, contrast began to become poor. Added to this was the lack of waves breaking on the delta, and although they were at a maximum immediately prior to low tide, there was still many days when there were very few or none at all.

From May onward then, photographs could only be taken between 1300 hours and 1630 hours and this had to coincide with low tide and the correct amount of cloud cover. This technique, while potentially useful in the summer months, became increasingly unreliable in autumn and winter. While nothing could be done about the lack of breakers, if photographs had not been taken looking northeast over the delta (i.e. into the sun for most of the day) the number of hours in a day suitable for photography would have been increased. So in the final analysis, the technique itself worked but the environment in which it was applied was inappropriate and therefore the results gained, in terms of usable photographs, were both time consuming and unreliable.

5.2.4 Rectification

i) Grid Construction

Rectification is a process used to eliminate variations in scale that are present in all oblique photographs. In general, rectification requires the identification of ground control points with known co-ordinates. These are fed into a computer and the image is then resampled and a rectified image of constant scale is obtained. In the case of this study however, this process was somewhat complicated by the absence of any ground control points on the sea surface. It was necessary therefore to create ground control points by constructing a perspective grid over the photograph. This was done using the Canadian grid method which is outlined by McNeill (1954).

This method allows the construction of a perspective grid using the horizon as a vanishing point. It is necessary to know the focal length (f') of the camera, the enlargement factor (m) of the photograph and the altitude (A) at which the photograph was taken. The grid is then constructed as shown in Figure 5.4.

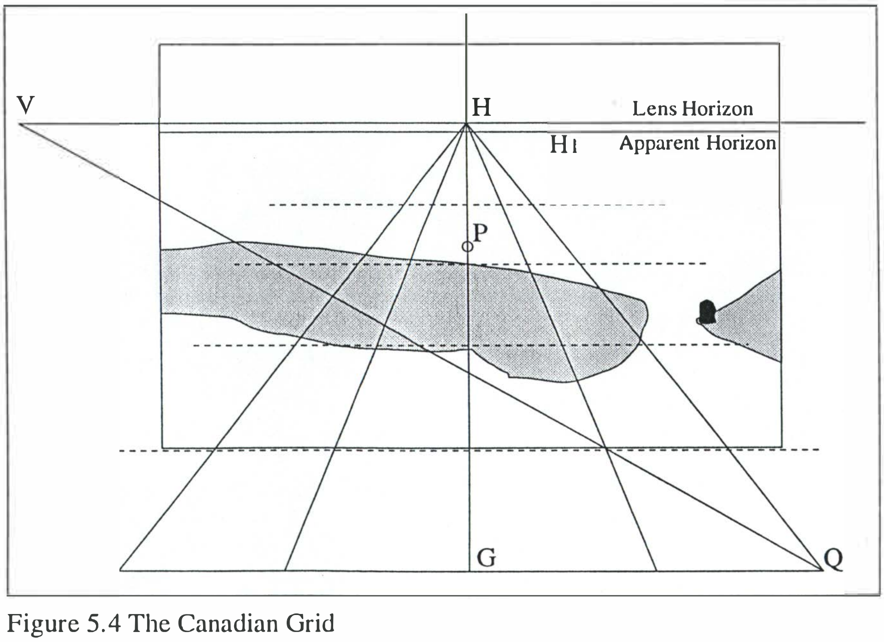


Figure 5.4 The Canadian Grid

A straight line is drawn through the apparent horizon and then a line perpendicular to this is drawn through the principal point (P). The intersection of these lines is H_1. Once this is done the apparent depression angle (q_1) between the optical axis of the camera and the apparent horizon is calculated where:

$$\tan \theta_1 = \frac{\overline{PH_1}}{f} \quad \text{(degrees)} \qquad \text{where } f = f'.m \quad (7)$$

Next the dip angle (D) between the apparent horizon (q_1) and the lens horizon (q) is calculated. This takes into account Earth curvature and atmospheric refraction:

$$D = 0.0295\sqrt{A} \quad \text{(degrees)} \quad (8)$$

The dip angle and depression of the apparent horizon (q_1) are then used to calculate the depression of the lens horizon (q):

$$\theta = \theta_1 + D \quad \text{(degrees)} \quad (9)$$

From this, the lens horizon can be drawn on the photograph. This is drawn parallel to the apparent horizon (q_1) at a distance:

$$\overline{PH} = f.\tan(\theta) \quad \text{(mm)} \quad \text{where H is intersection between the principal line and lens horizon}$$
(10)

It is then necessary to calculate the vanishing points (V):

$$\overline{HV} = f.\sec(\theta) \quad \text{(mm)} \quad (11)$$

The vanishing points are then marked on the photograph at a distance HV, either side of H.

The rest of the perspective grid can then be completed. The first constant scale line (G) is drawn anywhere in the foreground, parallel to the lens horizon. The scale (S) of this line is:

$$S = \frac{A}{\overline{HG}.\cos(\theta)} \qquad (12)$$

The sides of the ground resolution cells are then marked off along the first constant scale line at set intervals. This interval is arbitrary although resolution decreases as the interval is increased. A series of radial lines are then constructed from the lens horizon (H) through each of the interval marks. At this point a line is drawn through the vanishing point (V) to a convenient point (Q) in the foreground of the photograph. This line must pass through one of the interval marks on the first constant scale line (G). The rest of the grid can then be completed by drawing lines, parallel to the first constant scale line, at each intersection of QV and the radial lines drawn from the lens horizon (H).

The end result is a grid containing a number of quadrilaterals, diminishing in size with distance from the photographic site. On the ground these quadrilaterals would be represented as squares of equal size.

This method is not sensitive to altitude (A) but it is highly sensitive to the enlargement factor (m) and focal length (f'), which are multiplied to give f. An increase in either m or f' will significantly increase the length of the line HV. If this becomes too large it becomes difficult to construct the grid due to draughting limitations. Therefore there is a need to balance the focal length and enlargement of the photograph (i.e.: the resolution) with the ability to rectify the image using the Canadian grid method. For this study it was found that the optimal focal length was approximately 80 millimetres with an enlargement factor of just over five (5"x7" prints from a 35 mm negative). Even using these values however it was impossible to accurately draw the grid by hand because HV was typically in excess of 500 millimetres. To this end all grids were computer drawn in Archimedes *Vector*, where magnification allowed the construction of lines within an accuracy of 0.1 millimetres.

ii) Rectification

The photograph, with the grid drawn over it, was then scanned into Erdas *Imagine* so it could be rectified. Rectification is achieved by placing ground control points (GCPs) on the image. Each GCP consists of two pairs of x,y co-ordinates. Source co-ordinates, in this case expressed in pixels, and determined automatically by the computer and reference co-ordinates, which were arbitrarily determined in units of one. GCPs were placed at each intersection of the gridlines determined using the Canadian grid method.

Once the GCPs are entered and assigned reference co-ordinates, the required order of transformation is chosen. Erdas *Imagine* allowed transformations ranging from first order up to tenth order, where the order of transformation is given by the highest exponent used in the polynomial of the best fit line. In general lower orders are desirable because distortion between GCPs increases with transformation order and the results become less regular and predicable (Erdas, 1991). Higher order transformations also require a greater number of GCPs due to the increasing complexity of the transformation equation, an example of the best fit lines for first to fourth order transformations is given in Figure 5.5. The minimum number of GCPs required for a given order of transformation (t) is given by:

$$\text{GCPs} = \frac{(t+1)(t+2)}{2} \qquad \text{(Erdas, 1991)} \quad (13)$$

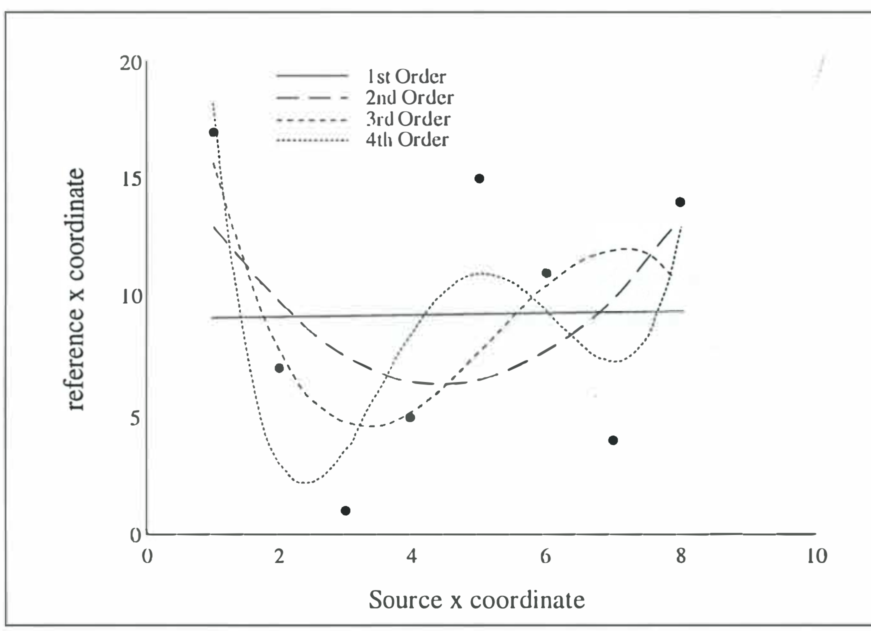


Figure 5.5 Examples of First to Fourth Order Transformations

The image was then resampled using the 'nearest neighbour' method, whereby the co-ordinates of the output pixel are assigned the source co-ordinates of the closest pixel, as shown in Figure 5.6. The root mean square (RMS) error is then determined. This is the distance, in pixels, of the reference pixel (x_i,y_i) from the retransformed pixel (x_r,y_r). RMS error can be calculated for individual GCPs or collectively for the entire retransformed image and is given by:

$$\text{RMS} = \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2} \qquad \text{(Erdas, 1991)} \quad (14)$$

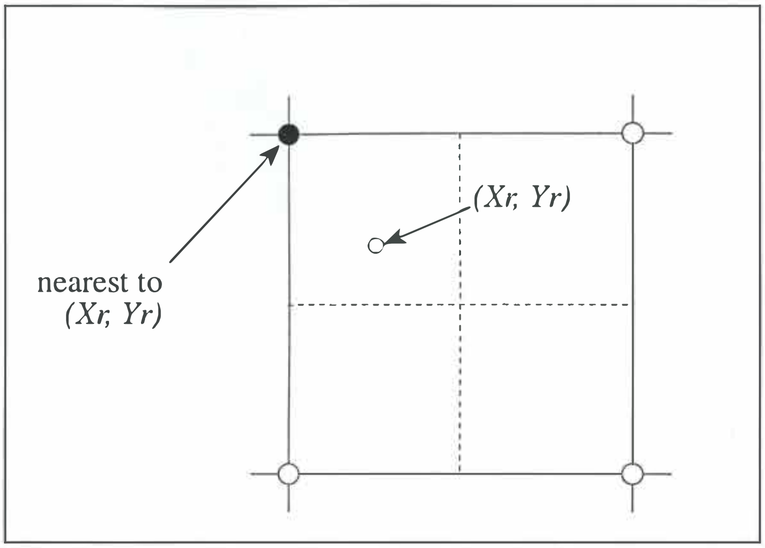


Figure 5.6 The nearest neighbour sampling method

The RMS error is reduced exponentially as the order of transformation is increased. But because lower order transformations are desirable it becomes a trade off between total RMS error and the distortion of each pixel. Where the size of the pixels on the ground is known, RMS error can be converted to known units, for example, metres. The number of GCPs used, the order of transformation and total RMS error associated with each image used in this study will be given in section 5.3.

5.3 Changes in the Avon-Heathcote Ebb Tidal Delta

5.3.1 Introduction

This section presents the results of ten time exposure photographs taken of the Avon-Heathcote ebb tidal delta between 27 December 1993 and 26 August 1994. Figures 5.8a-c show a summary of the ebb tidal delta positions for each of the study days while Figures 5.9a to 5.18a present the actual photographs taken while Figures 5.9b to 5.18b are the corresponding rectified images. Because the rectified images where scanned into Erdas *Imagine* and then printed out before being photocopied for this thesis, considerable detail has been lost on some of the images. This is particularly severe in the cases of Figure 5.11b (20 February), Figure 5.13b (28 April), Figure 5.15 (14 June) and Figure 5.18 (26 August). In these cases lines have been drawn into to represent the seaward margin of the ebb tidal delta. Details of the photographic conditions for each day are given in Table 5.2.

Date	Time	Low Tide*	Focal Length (mm)	Appar-ture	Cloud Eigths	Light (EV)	Breaker Height (m)
27/12	1215	1130	105	16	4	-	1.0
06/01	1810	1930	105	16	1	-	1.5
20/02	1715	2000	80	11	8	-	0.5
13/04	1315	1300	80	11	6	15	0.6
28/04	1245	1230	80	16	5	17	0.5
15/05	1445	1500	80	11	8	14	0.5
14/06	1430	1545	80	11	7	16	0.5
11/07	1330	1300	80	16	2	15	0.4
29/07	1530	1745	80	16	1	15	0.6
26/08	1400	1530	80	16	2	16	0.5

* Low tide at Ferrymead Bridge - Due to propagation up the estuary low tide at the mouth would be earlier than this by about 30 mins.

Table 5.2 Photographic Conditions

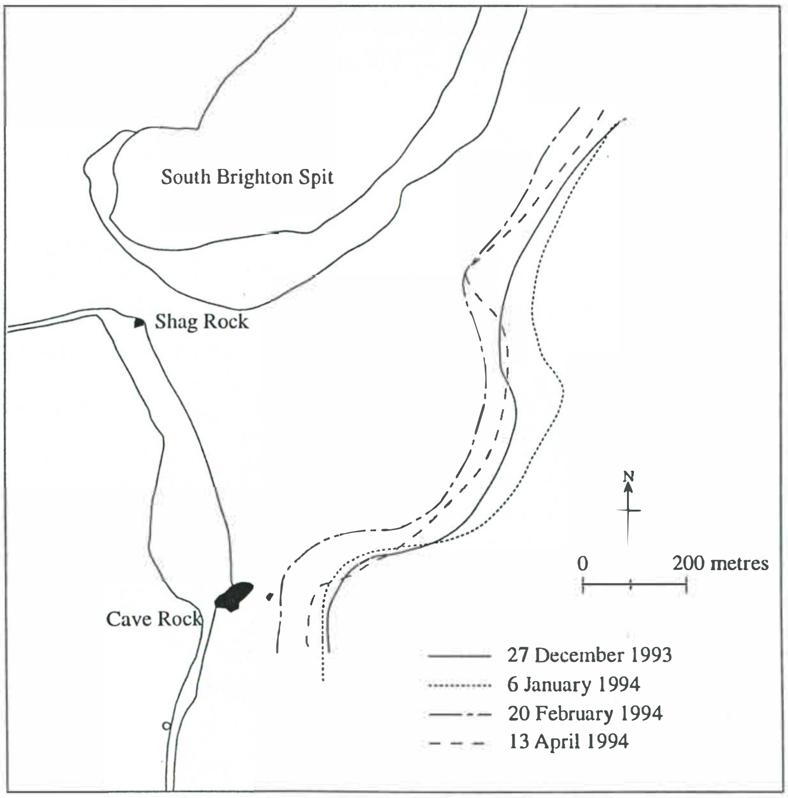


Figure 5.8a Delta margin positions, December 1993 - April 1994

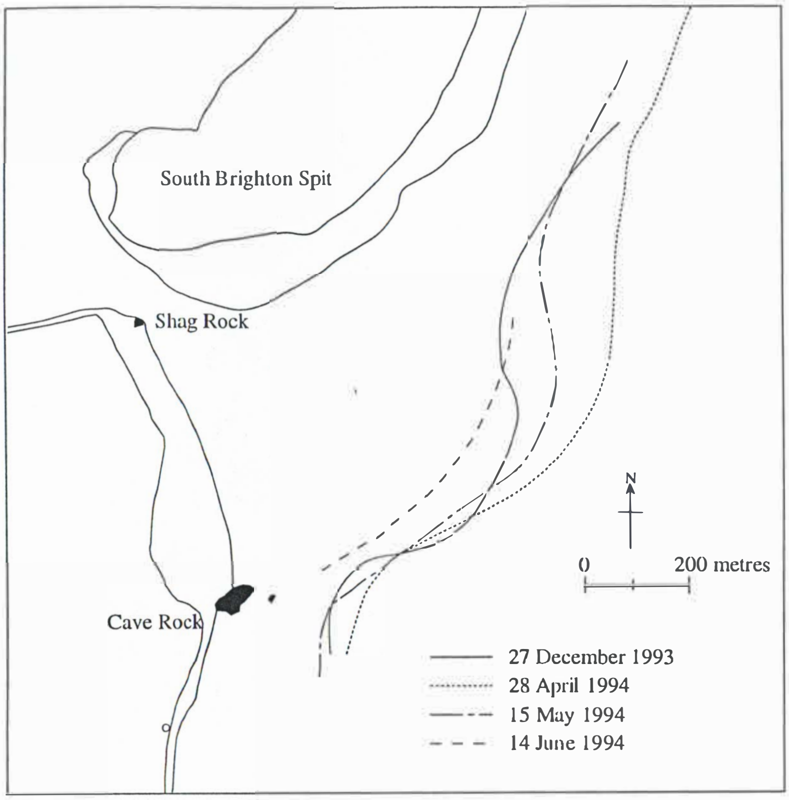


Figure 5.8b Delta margin positions, April 1994 - June 1994

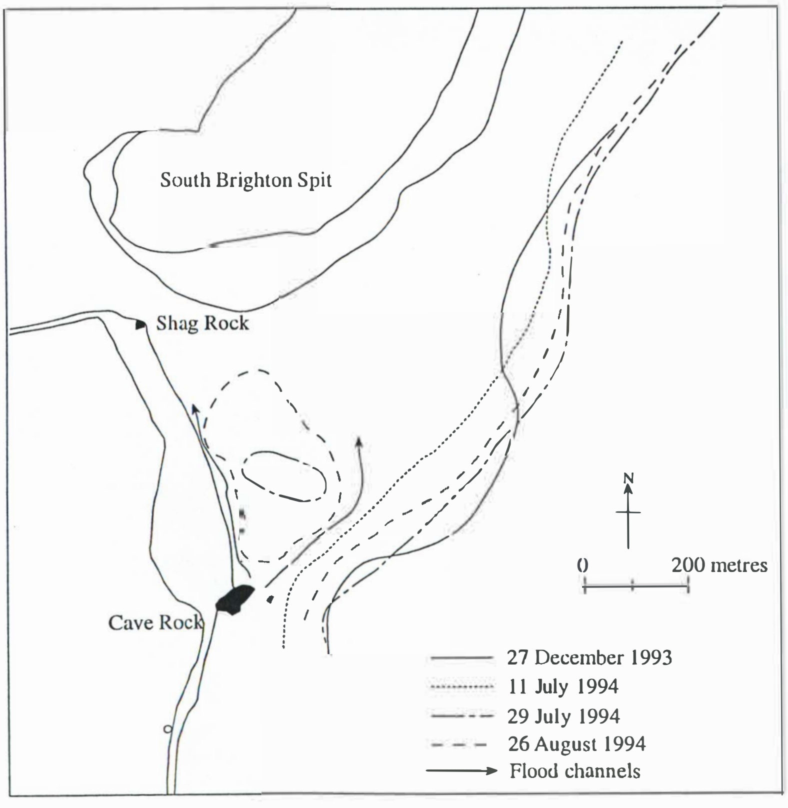


Figure 5.8c Delta margin positions, July 1994 - August 1994

Before presenting changes in the delta margin however, Figure 5.7 is a map of the delta showing its main morphological, drawn from the December and January photographs. It can be seen that, like the hydrographic survey shown in Figure 5.1, that the delta had a strongly crescentic form, with the intensity of breaking (Figure 5.10) representing the rapid transition from relatively deep water to shallow water over the delta terminal lobe. South of the main ebb channel a large shoal lay just beneath the water surface. There was also a shoal north of the ebb channel, although this lay in deeper water and appeared to be smaller. Also north of the ebb channel was a swash bar, visible at low tide, very close to the spit and this was dissected by a shallow channel.

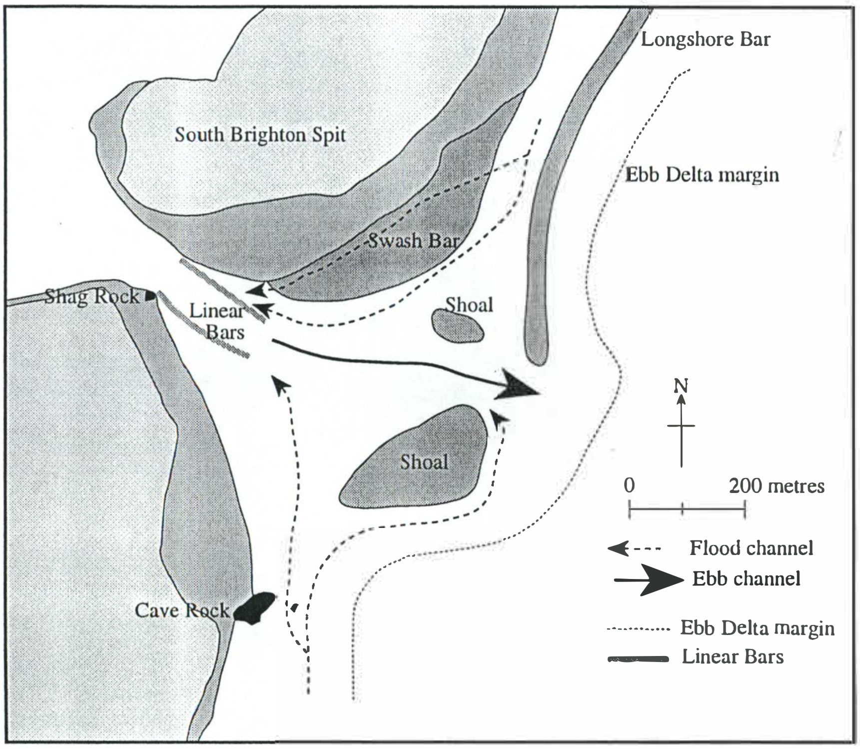


Figure 5.7 Ebb tidal delta morphology derived from January 1994 time exposure

Figure 5.9 Delta morphology, 27 December: a) photgraph b) rectified image

Figure 5.10 Delta morphology, 6 January: a) photgraph b) rectified image

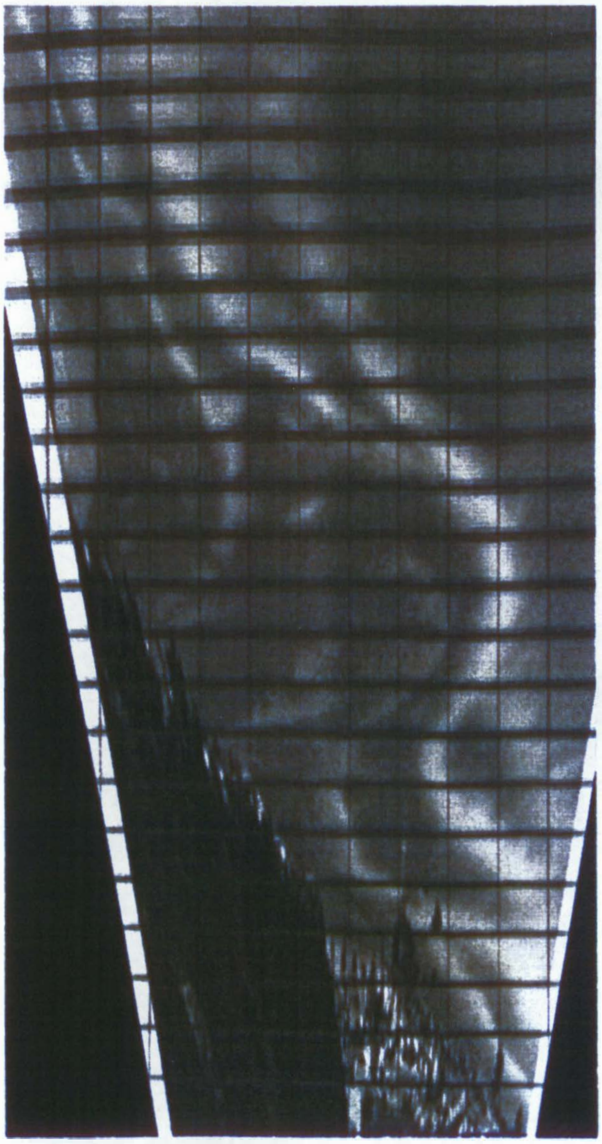


Figure 5.11 Delta morphology, 20 February: a) photgraph b) rectified image

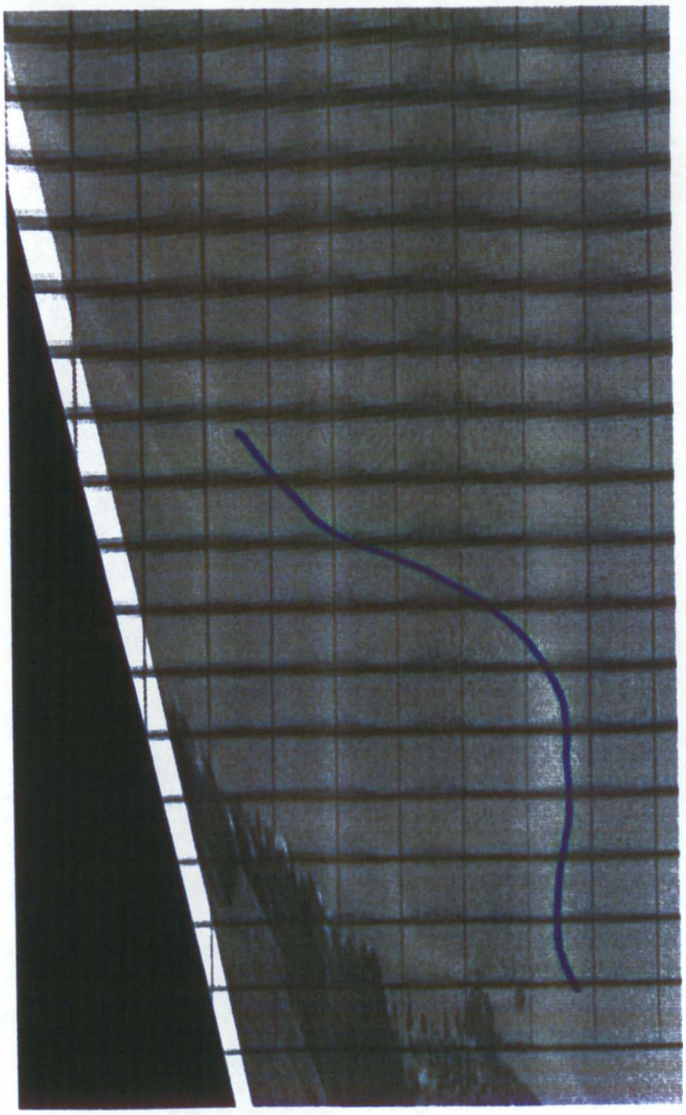


Figure 5.12 Delta morphology, 13 April: a) photgraph b) rectified image

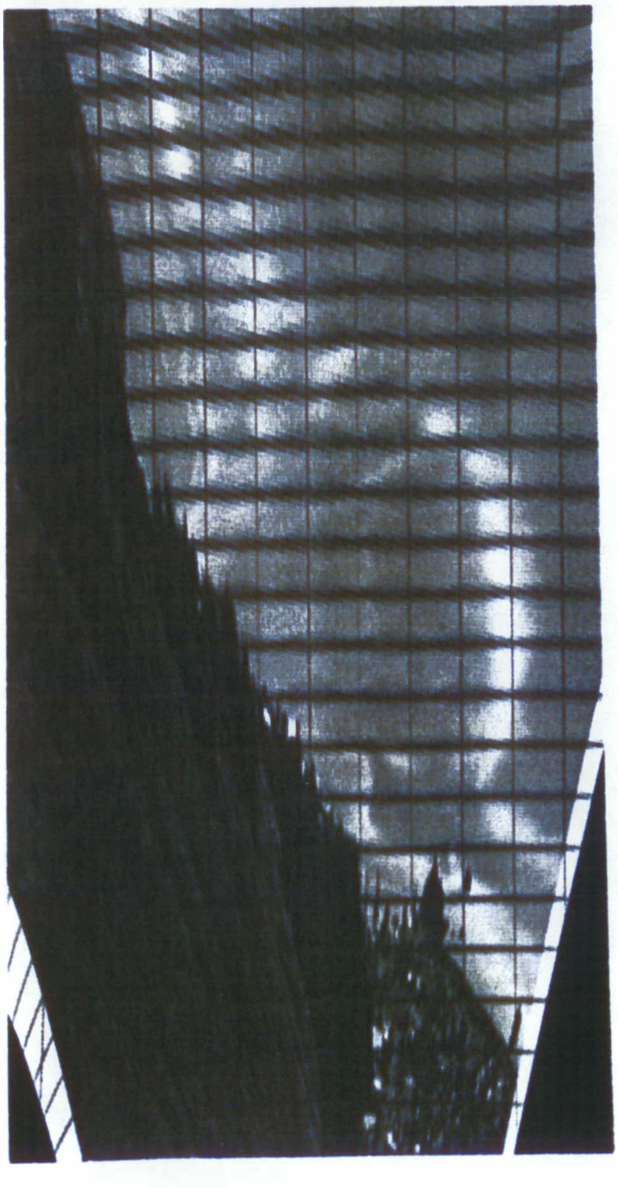


Figure 5.13 Delta morphology, 28 April: a) photgraph b) rectified image

Figure 5.14 Delta morphology, 15 May: a) photgraph b) rectified image

Figure 5.15 Delta morphology, 14 June: a) photgraph b) rectified image

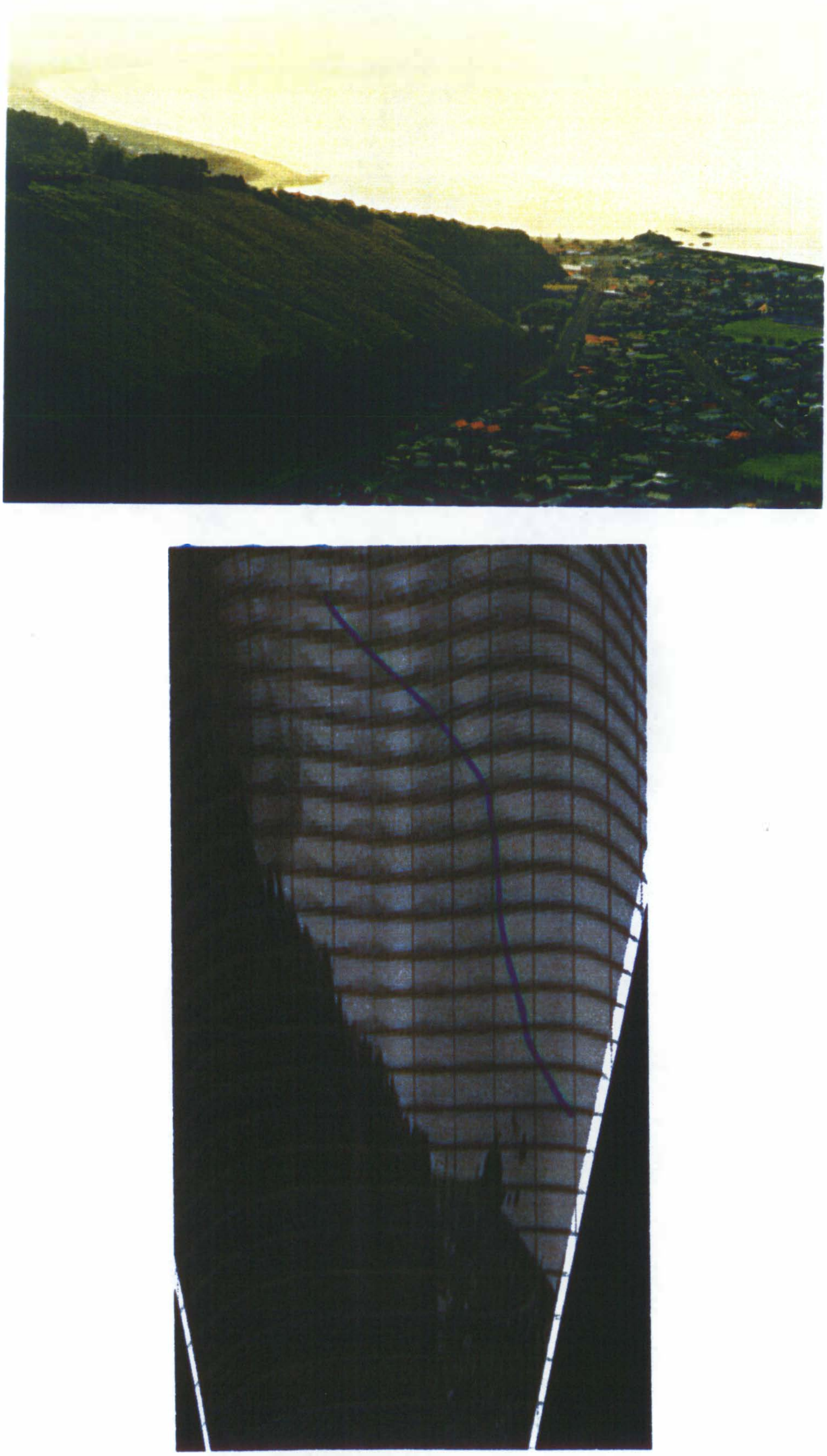
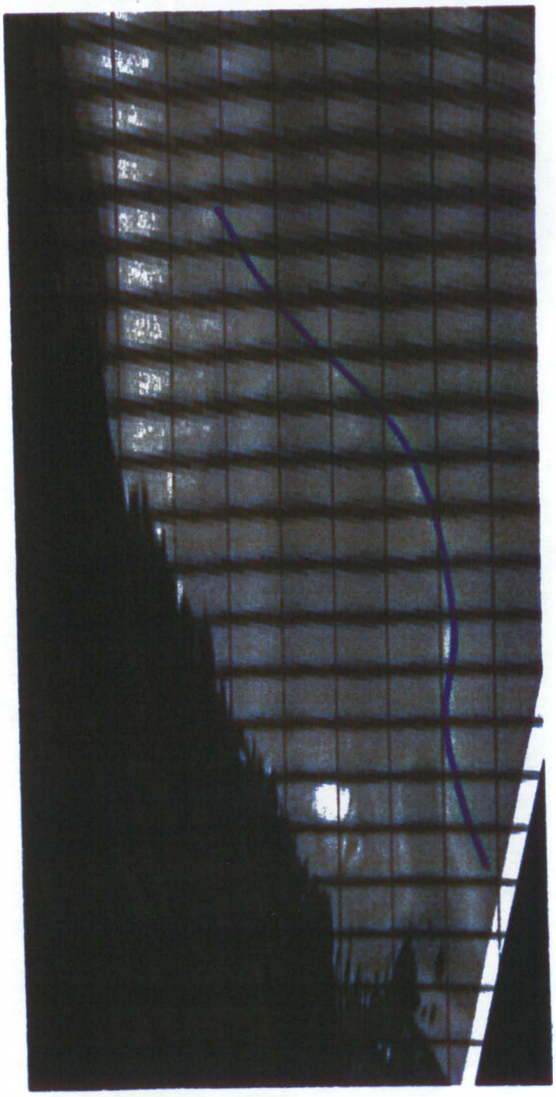


Figure 5.16 Delta morphology, 11 July: a) photgraph b) rectified image

Figure 5.17 Delta morphology, 29 July: a) photgraph b) rectified image

Figure 5.18 Delta morphology, 26 August: a) photgraph b) rectified image



It can be seen that the main ebb channel had a east-southeast orientation and linear bars are present on both sides of the channel margins. Two major marginal flood channels can be seen. The first ran north-northeast from the main ebb channel, and north of this graded into the offshore bar system. The other channel ran southeast past Cave Rock, cutting through the bar system and out to sea, just south of Cave Rock.

5.3.2 Changes in the Seaward Margin of the Delta

Owing to a lack of breaking waves, only limited information can be gained from most of the rectified images. In each case however, it is possible to identify the seaward extend of the delta terminal lobe and the location of the delta alongshore. For each of the days the delta position is given as the distances east and south (or north) of the most seaward point from Shag Rock. This gives a fair representation of overall delta position and is a point easily located on all the rectified images. These positions are given in Table 5.3.

Date	Distance East (m)	Distance Nth-Sth (m)
27/12/93	910	220 South
06/01/94	1025	70 South
20/02/94	840	130 South
13/04/94	890	70 South
28/04/94	1130	110 South
15/05/94	1005	160 South
14/06/94	900	50 South
11/07/94	990	140 North
29/07/94	1080	40 South
26/08/94	1030	70 North

Table 5.3 Distance of Delta from Shag Rock

From Figure 5.8a and Table 5.3 it can be seen that on December 27 (Figure 5.9) the delta had a strongly crescentic shape, the apex of which was 910 metres east, and 220 metres south, of Shag Rock. Ten days later, on January 6 (Figure 5.8a, Figure 5.10), the delta still had the same shape but the terminal lobe was around 100 metres further east and had moved north by 50 metres. By February 20 (Figure 5.8a, Figure 5.11), 37 days later, the delta is shown to be considerably closer in shore (840 metres) and had moved a further 40 metres north. This northward movement is also shown on April 13 (Figure 5.8a, Figure 5.12)), although the delta had moved 50 metres east. 15 days later, on April 28 (Figure 5.8b, Figure 5.13), the margin of the delta was 1 130 metres east of Shag Rock and the crescentic form had become wider and skewed in a northward direction. This skew was become more pronounced by May 15 Figure 5.8b, Figure 5.14), although the delta was 125 metres closer inshore than on April 28 (Figure 5.8b, Figure 5.15).

Due to an almost complete lack of breakers on June 14, it was difficult to locate the position of the entire delta margin. From the information available on the image however the delta was close inshore, at 900 metres east of Shag Rock and only 50 metres south. The July 11 image (Figure 5.16c) is interesting in that it shows the delta to have lost almost all of its characteristically crescentic shape. Most of the delta margin was also very close inshore although the apex itself was 900 metres east of Shag Rock. Also interesting on July 11 was that the delta was 140 metres north of Shag Rock. The delta however had moved south again by July 29 and had regained some of its crescentic shape. This was further enhanced during August although the delta had moved to a position north of Shag Rock once again.

It can be seen then that throughout the study period the delta showed significant shifts in both its onshore/offshore position and alongshore position, with a generally northward moving trend. Also between December 27 and July 11 the delta became increasingly flat and a northward skew become more pronounced.

Because the location of the delta has been inferred from the waves breaking on it, it is tempting to attribute the variations in delta location to differences in wave height on individual days. There is no question that, in general, higher waves would break further offshore although, when breaker height and distance offshore are regressed in Figure 5.19, it can be seen that there is no relationship ($r^2 = 0.001$) between the two variables. In any case, soundings in this area show that seaward of the delta, gradients are as high as 1:40 (Hydrographic Office, Royal New Zealand Navy, 1976) This means that variations due to differences in wave height would be expressed within a very small distance.

Breaking can also be induced by an opposing current. It is possible then, that photographs taken prior to low tide, when waves face an opposing ebb current, the delta would be shown to be further offshore. However when these to variables are plotted against each other, as in Figure 5.20, it can be seen that there is virtually no relationship ($r^2 = 0.007$). It also possible that the water level at the time of photography could have an influence on where waves were breaking. It however is not possible to accurately account for this because all photographs were taken close to low tide and the recorder at Ferrymead Bridge does not give low tide readings.

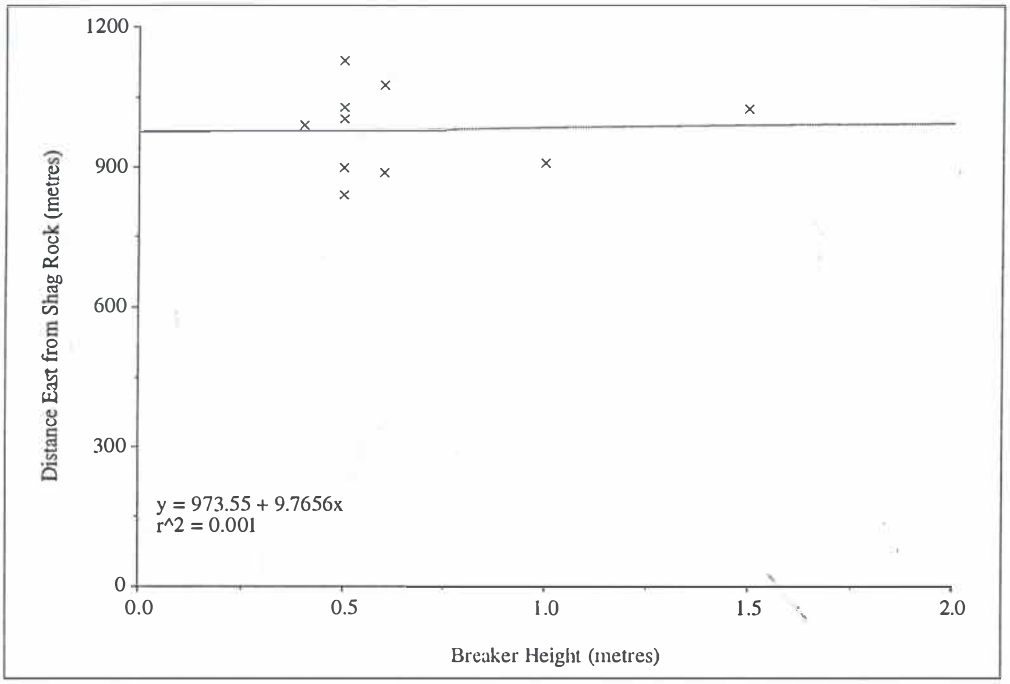


Figure 5.19 Relationship between wave height and offshore distance of delta

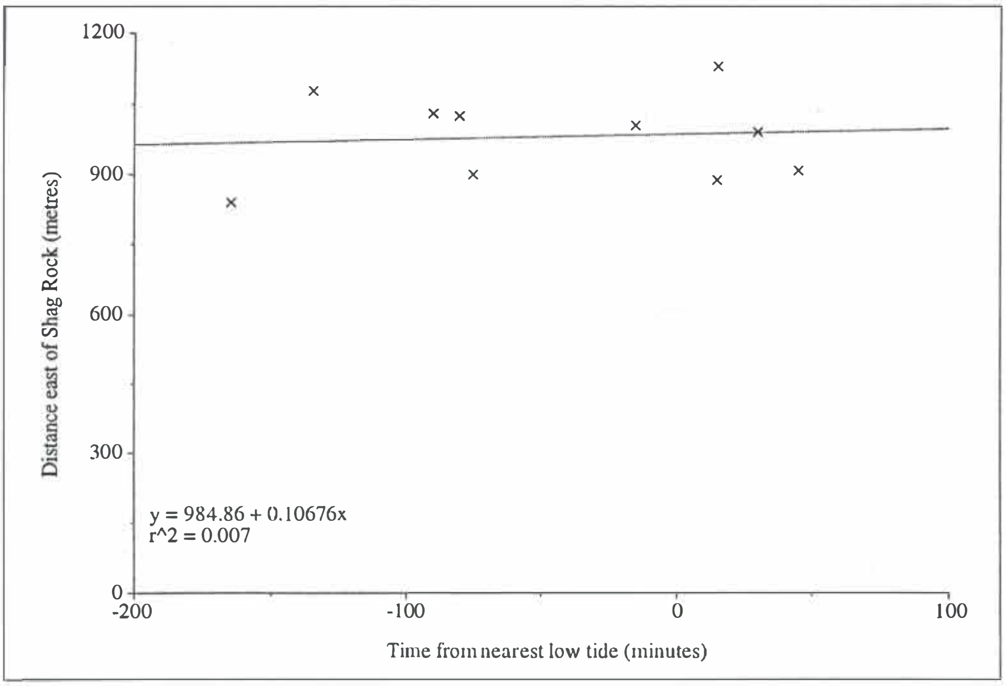


Figure 5.20 Relationship between delta location and time from low tide

It is also unlikely that errors in rectification can explain the difference because, from Table 5.4, it can be seen that RMS errors were very low, with the maximum only being 6.7 metres, on 11 July.

Date	Min. no. of GCPs	GCPs Used	Transorm. Order	RMS Error (m)
27/12/93	15	142	4	1.2
06/01/94	15	194	4	0.9
20/02/94	15	145	4	0.8
13/04/94	15	150	4	0.5
28/04/94	15	166	4	0.7
15/05/94	15	153	4	0.6
14/06/94	15	155	4	1.0
11/07/94	15	121	4	6.7
29/07/94	15	148	4	0.8
26/08/94	15	119	4	0.5

Table 5.4 Rectification Details

5.3.3 Channel Positions

The only two images that give any detailed information about the channel positions are those for December 27 (Figure 5.9) and January 6 (Figure 5.10). The main ebb channel ran northeast out of the estuary and then turned and ran north-northeast. Near the southern delta margin there is a channel which runs southeast past Cave Rock, seaward of the small island. From the rectification for January 6 rectification it can be see that this southern channel is separated from the main ebb channel by a shoal, suggesting that it is a flood channel. The fact that the tide sets on the Canterbury coast from the south (Goring:1991) further supports this hypothesis.

From January onwards the location of the main ebb channel can not be discerned from any of the photographs. Parts of the southern flood channel however, can be seen on 13 April (Figure 5.12), 15 May (Figure 5.14), 29 July (Figure 5.17) and 26 August (Figure 5.18). It can be seen from these images that, in the vicinity of Cave Rock, this channel gradually moved 20-30 metres closer inshore between December 1993 and August 1994.

5.4 Summary

Time exposure photographs of waves breaking on the Avon-Heathcote ebb tidal delta were taken between December 1993 and August 1994. Although frequent attempts were made to take photographs, only 10 usable images were obtained due to the frequency of insufficient breakers and/or poor lighting conditions. The 10 photographs used in this study were rectified using the Canadian grid method and maps were drawn of the seaward margin of the ebb tidal delta. These showed that the delta became progressively flatter throughout the study period and that there was a general trend for the delta to move northward. Very little data regarding the seaward delta channels was obtained although it was demonstrated that the southern flood channel moved inshore throughout the study period.

Chapter 6: Processes

6.1 Introduction

This chapter presents data on the processes that were likely to have had some bearing on the changes at the mouth of the Avon-Heathcote estuary as discussed in Chapter Four and Chapter Five. It includes flow data for the Avon and Heathcote rivers, wind and swell predictions made by the New Zealand Meteorological Service, and tide data recorded at the Ferrymead Bridge.

6.2 Rivers

This section presents data on the discharge of the Avon and Heathcote rivers between October 1993 and July 1994. Neither data sets relates to the mouths of the rivers, rather for the Avon River recordings are taken from the Gloucester Street Bridge and for the Heathcote from Buxton Terrace, as shown in Figure 6.1. The data presented is the mean flow for the previous 24 hours and has been converted from litres per second to cubic metres per second (cumecs).

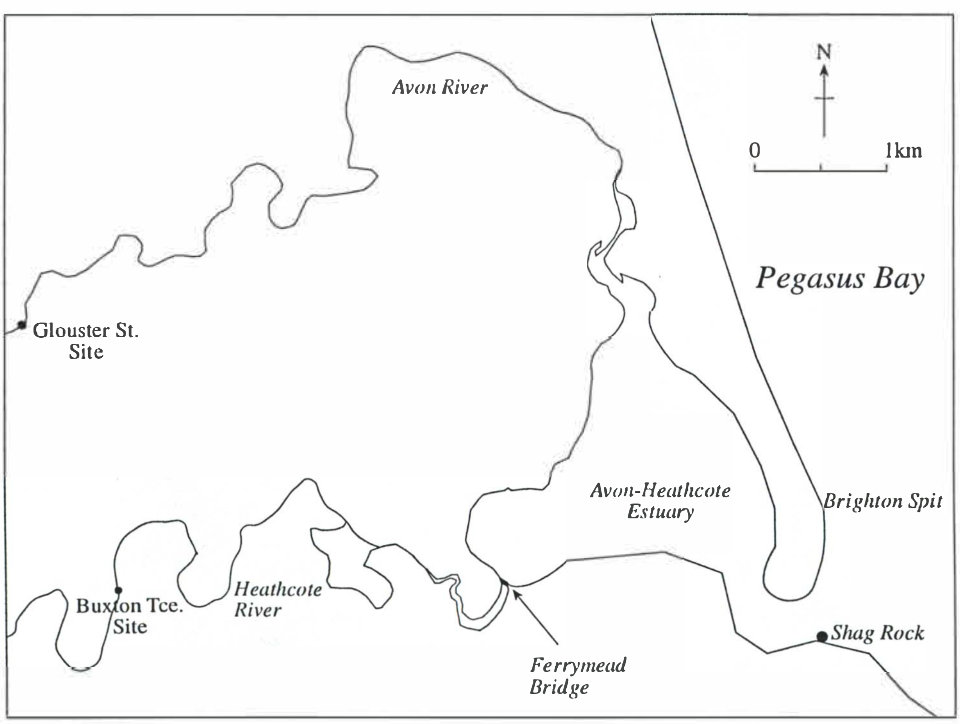


Figure 6.1 Location of river flow recorders

Figure 6.2 shows the discharge for the Avon River at the Gloucester St Bridge. Mean flow at this site, calculated from data collected between January 1992 and August 1994, was 1.97 cumecs. It should be noted that this is considerably less than the value calculated by Mawson (1972) who obtained a value of 3.25 cumecs at the mouth of the Avon River. It can be seen in Figure 6.2 that for most of this study period the river had flows around the mean of 1.97 cumecs. Flow only exceeded 4.0 cumecs (twice the mean flow) on four occasions, with only the July event approaching flood proportions. This was a three day event, with the highest mean daily flow being 9.16 cumecs on 26 July, and was in response to high rainfall in Christchurch where 142 millimetres fell in 72 hours. The other high flows were on 29 November 1993 (4.41 cumecs), 19-20 March 1994 (4.86 and 4.04 cumecs respectively) and 18 July 1994 (4.33 cumecs).

The Heathcote River displayed a similar trend over the study period, as shown in Figure 6.3. Mean flow at this site was calculated to be 0.66 cumecs (1992-1994 data) and this is also considerably lower than Mawson's (1972) estimate of 1.13 cumecs. High flows (i.e.: greater than 1.32 cumecs) only occurred on five occasions. There was a three day event between 11-13 May, where maximum mean flow reached 2.92 cumecs on 12 May and similarly, between 27-29 June, mean flow exceeded 1.32 cumecs for three days, reaching a maximum of 2.33 cumecs. The remaining high flows were on 2 July (1.39 cumecs), 5 July (1.46 cumecs) and 8 July (1.32 cumecs).

Placing these flows in the context of longer term data from January 1992, the Heathcote flows were relatively high during this study period. Flow exceeded 1.0 cumecs on a total 22 days (out of 314 days) while between January 1992 and September 1993 there were no occasions where 1.0 cumecs was exceeded. Similarly between January 1992 and September 1993, flow only exceeded 4.0 cumecs on six days, three of which occurred during the August 1992 storm, where a maximum flow of 9.39 cumecs was recorded for 28 August 1992. However the data presented here for the August 1992 storm are quite different for the Heathcote River flows cited by Hicks (1993). Using data from the same site on the Heathcote River (at Buxton Terrace), Hicks (1993) presents data that is consistently in excess of 10 cumecs between 27-31 August 1992. The data presented by Hicks (1993) for the Avon River, at Gloucester Street, is consistent with the data used in this study.

In summary then, the flow rates in the Avon and Heathcote rivers both seemed to be relatively high during this study period. Although large floods were not frequent the maximum flow rate in the Avon River at the end of July 1994 was of the same magnitude as the August 1992 storm, although for a shorter duration.

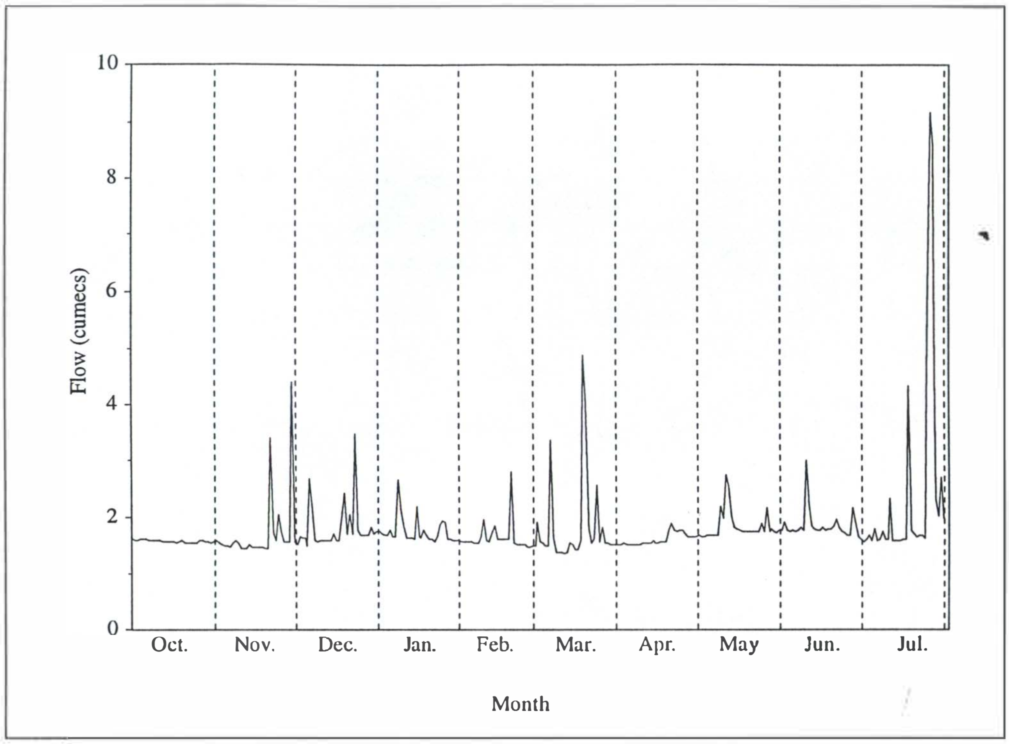


Figure 6.2 Avon River Flow at Glouster Street Bridge, October 1993 -July 1994

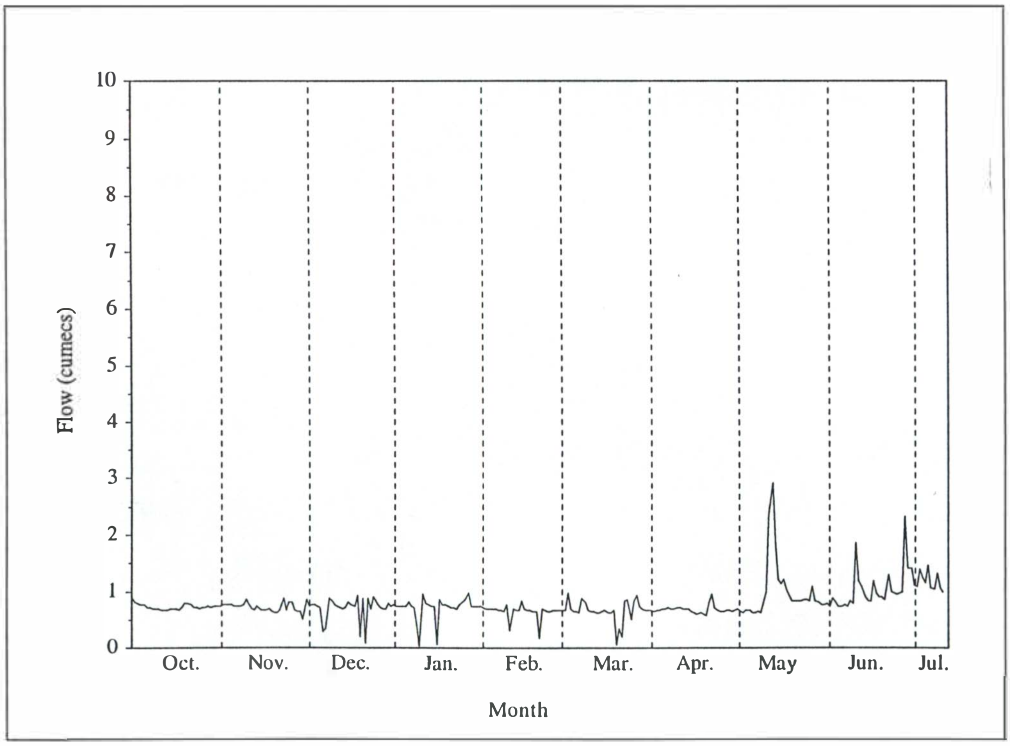


Figure 6.3 Heathcote River flow at Buxton Terrace, October 1993 to July 1994

6.3 Wind

This section presents data from New Zealand Meteorological Service predictions for Pegasus Bay. Daily wind data are also available from the climate station at Christchurch Airport but this is some distance inland from the study site and is not representative of conditions at the coast (Brown, 1976). The purpose of analysing wind data in this study is to elucidate the likely trends in locally generated waves, which are not included in the swell predictions presented in the following section. For the purposes of this study then, the use of offshore wind predictions is satisfactory. Figure 6.4 shows wind speed and direction for January to June 1994. An error was made in the collection of the July and August data, so it is not presented here.

The beaches of southern Pegasus Bay face southeast which means that the only locally generated wind waves that will be incident at the shore are those generated in the easterly quarter, that is by northeast, east and southeast winds. Both Burgess (1968) and Brown (1976) demonstrated that locally generated northeast wind waves are an important component of the southern Pegasus Bay wave environment and that the tend to be small, steep and have short periods. Because small waves can travel further up the beach before breaking, this means that, in sufficient numbers, they have the potential to cause significant erosion.

From Figure 6.4 it can be seen that, in the four months between January and April, the frequency of northeast winds was very high accounting for 40 percent, 48 percent, 37 percent and 47 percent of the predictions respectively. They tended to be mild at 15-20 knots with the exception of February and March which also had significant proportions of 5-10 knot winds. The were virtually no northeast or easterly winds during May although the frequency increased again during June, with winds from the easterly quarter accounted for a third of the total predictions.

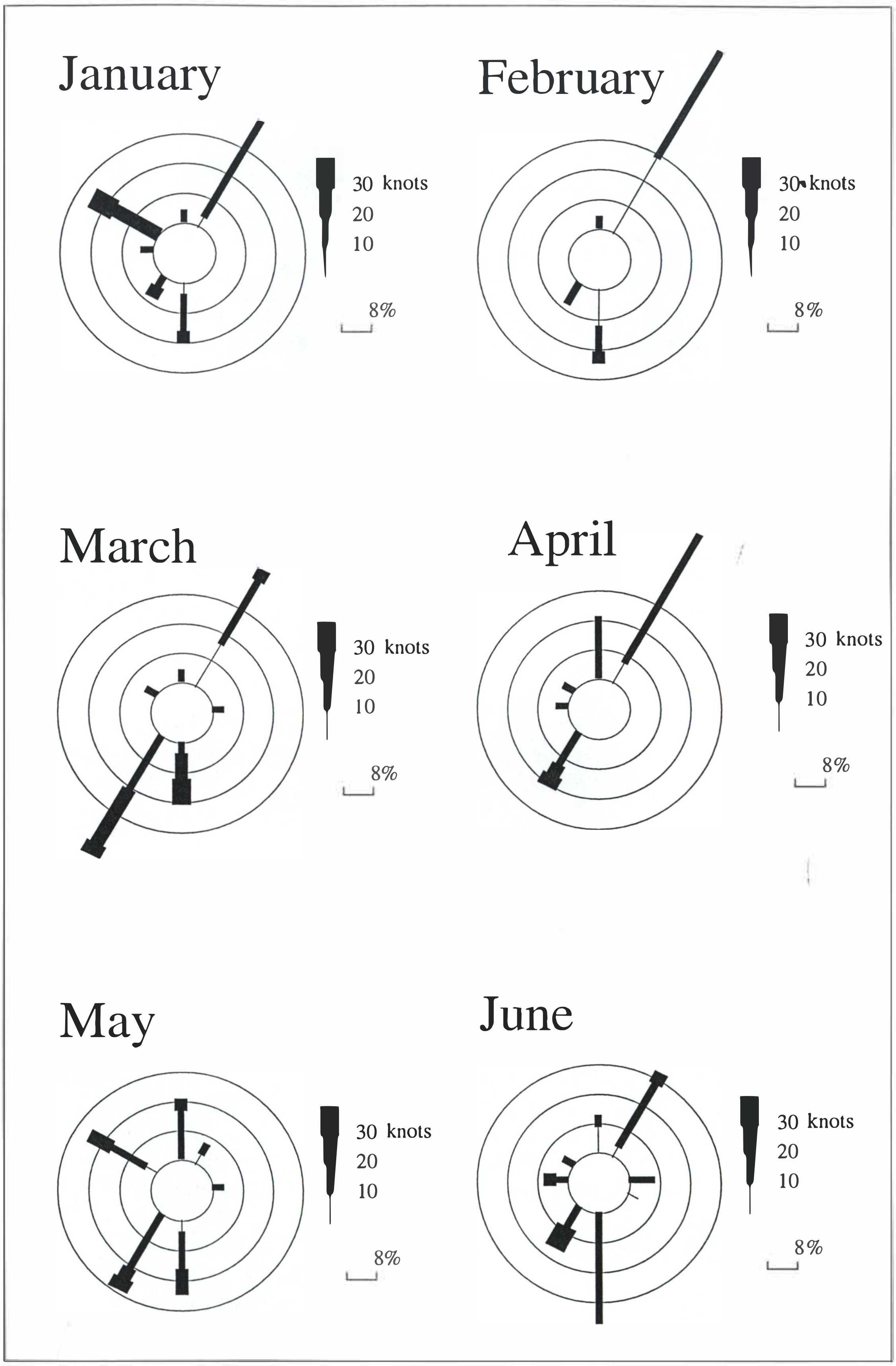


Figure 6.4 Wind Roses for January to June 1994

6.4 Waves

The wave data presented in this section comes from the swell predictions made for Pegasus Bay by the New Zealand Meteorological Service. As pointed out in Chapter Three, waves arriving at the beach in Southern Pegasus Bay are subject to intense modification due to refraction. The swell data therefore, in addition to being only predictions, are likely to be different than what was actually incident at the shore. This however can be compensated for by allowing for the transformations due to refraction. Direct wave observations were made by a volunteer for the Canterbury Regional Council from May onwards. There were however large gaps in this data so it has not been used.

Figure 6.5 shows the predicted swell for Pegasus Bay between January and August 1994. In general it can be seen that swell from the northeast, east and southeast rarely reached 3.0 metres. Southerly and southwesterly swells however were frequently 2.0 metres or higher with maximums of 4.0 metres being predicted in March and May.

The prevailing swell in January was northeast 1.0-2.0 metres, with some larger swell from the south and southwest. During February however, over 50 percent of the swell was from the south, with the remainder being northeast, east and southeast. For March, April and May the prevailing swell directions were southwest and south, most of which was than 2.0 metres or more. There was however significant amounts of northeasterly swell during these three months, particularly in the case of May. In June there was a decrease in southwest swell, although there was an increase in swell from the south (34 percent), with the remainder sourced from the east and southeast (27 and 23 percent, respectively). July and August were similar with swell from the northeast, east, south and southwest. The majority of swell during July however was 3.0 metres or more, while in August swell was mainly 1.0-2.0 metres.

Comparing these predictions with ships observations between 1953 and 1980, it can be seen that the data sets are quite different (Table 6.1). Overall the 1994 predictions showed considerably more northeast and southwest swell than the 1953-1980 observations and less east, south and southeast swell. Part of this difference can be explained by the inclusion of westerly and northwesterly swell observations for the 1953-1980 data, of which there were none for the 1994 predictions. The remainder of the differences, which are substantial, can therefore be explained either as 1994 having a different swell regime than the mean

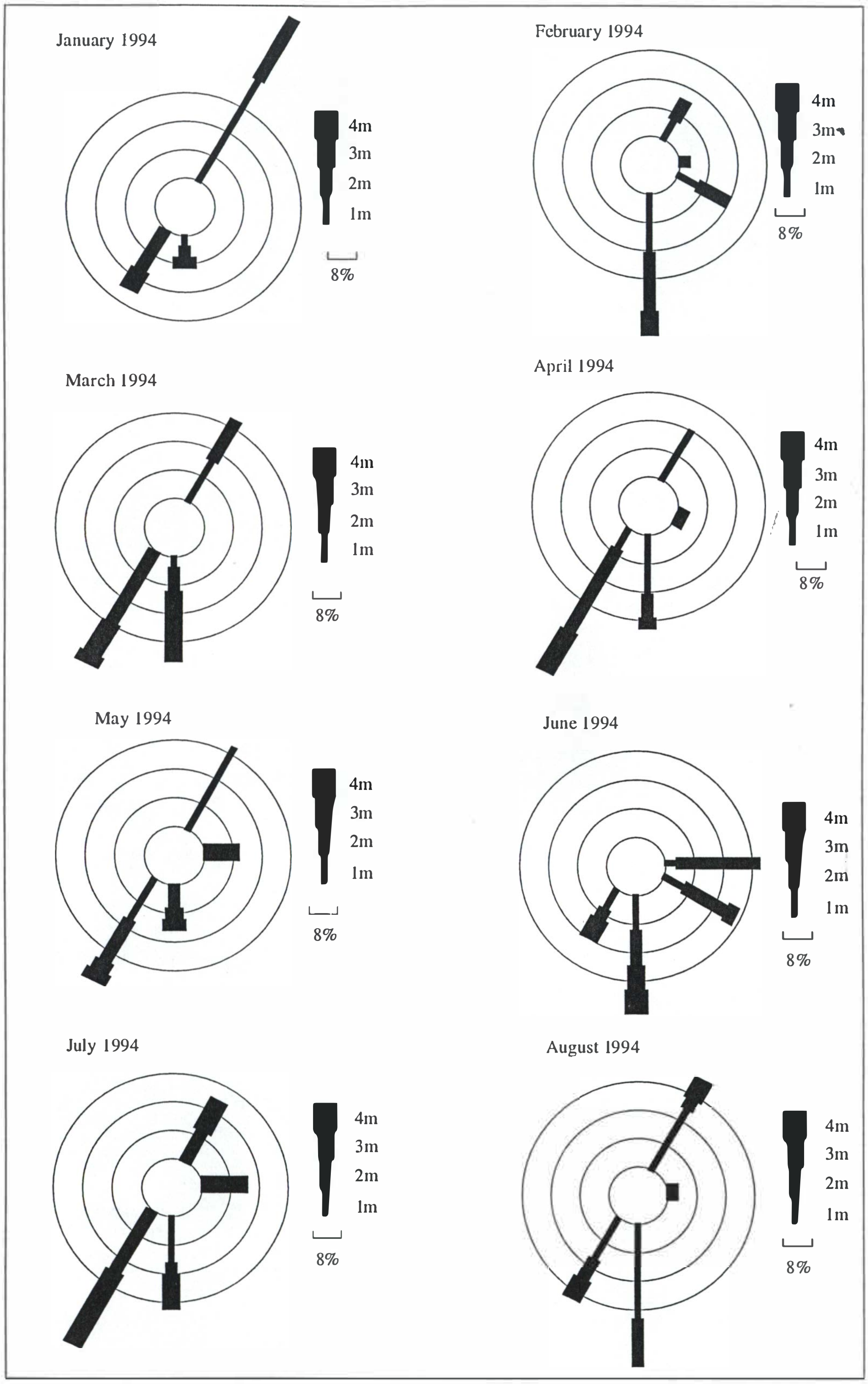


Figure 6.5 Swell Roses for January to August 1994

conditions for 1953-1980 or that the predictions contain errors. It is not possible to precisely evaluate which situation applies here, although it is likely that the 1994 data contains elements of both.

Season	Direction	Frequency (%) 1953-1980	Frequency (%) 1994
Summer	Northeast	25.4	48.0
	East	14.9	2.0
	Southeast	9.8	6.0
	South	24.9	28.0
	Southwest	6.6	12.0
Autumn	Northeast	19.5	25.0
	East	14.4	3.6
	Southeast	11.6	1.2
	South	34.8	26.2
	Southwest	10.0	38.1
Winter	Northeast	13.7	18.3
	East	14.4	14.0
	Southeast	12.0	5.4
	South	41.3	32.3
	Southwest	8.4	29.0

Table 6.1 Offshore Swell Predictions: 1953-1980 and 1994

Despite the potential errors however, it can be seen that there was a characteristic decline in the incidence of northeast swell and a corresponding increase in southerly swell toward winter. Swell height is also shown to increase toward winter and this is consistent with the findings of Burgess (1968) and Brown (1976) whose studies included observations of waves incident at the beach.

In addition to the swell climate, between January and April there would have also been a significant locally generated component of small, steep, short period waves from the easterly quarter, as discussed in the preceding section.

6.5 Tides

The high tide levels incident at Ferrymead Bridge for this study period are shown in Figure 6.6. Low tide readings can not be used at this site because, except in the case of very high low tides, the pressure transducer is not in any water at low tide (D. Carver, Wastewater Unit, Christchurch City Council, *pers. comm.*). As a result of this the low tide readings shown in Figure 6.6 all appear to be at around the same height.

The monthly cycle of apogean and perigean tides discussed by Goring (1991) is clearly shown in Figure 6.6. In Table 6.2, the period in days between each extreme high tide has been calculated. Ignoring the two lowest numbers for

January (21 days) and August (15 days), a mean of 28.6 days is obtained for the return time of the highest high tides. The cycle of spring and neap tides can also be seen in Figure 6.2 and they are represented as the minor peaks between the perigean tides, with a return period of approximately 14 days.

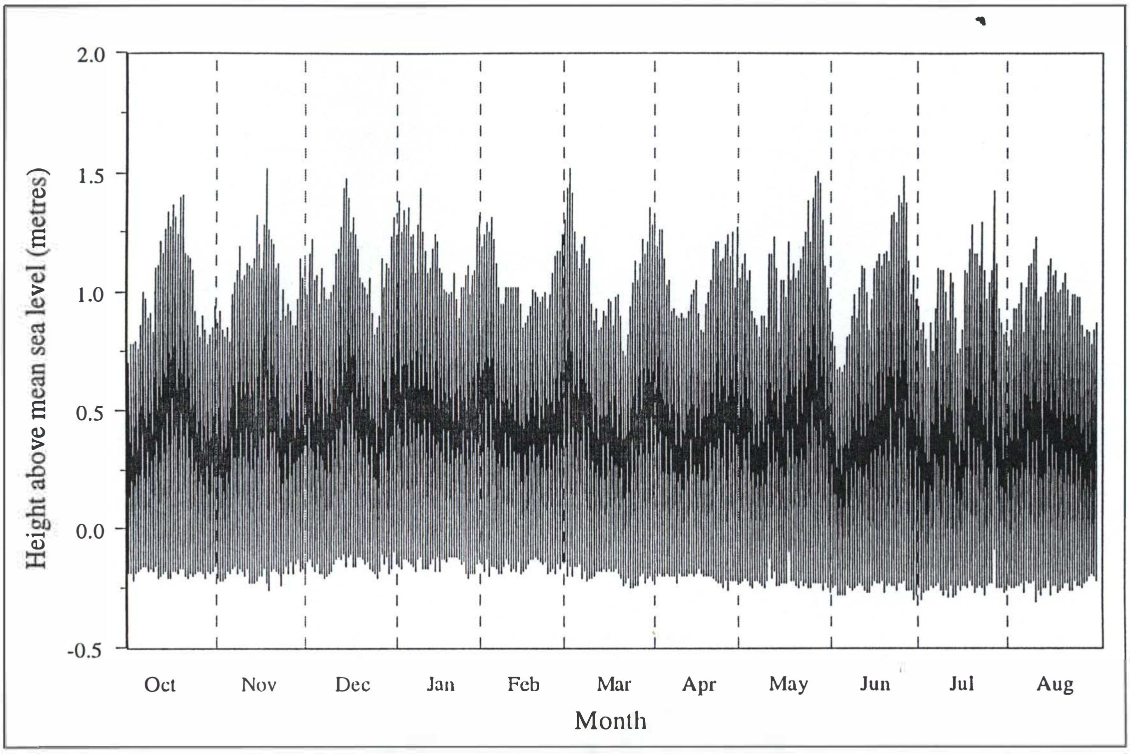


Figure 6.6 High tide levels at Ferrymead Bridge: October 1993 - August 1994

Goring (1991) also demonstrated that there is a 6-7 month cycle of very high tidal ranges and very low tidal ranges due to the coincidence of perigean and spring, and apogean and neap tides. For this study period, very high tides were predicted for November 1993 and May 1994. It can be seen in Table 6.2 that this was the case with the November tide reaching 1.521 metres and the May tide reaching 1.503 metres. In the case of May, it can also be seen that the perigean tides were followed in June by very low apogean high tides, with the lowest being only 0.664 metres on June 4.

Table 6.2 also shows that the high tide levels incident at Ferrymead Bridge were most strongly influenced by astronomical events. Air pressure, which has the effect of raising water levels by 0.0085 metres for every millibar under 1013 millibars (Oliver and Kirk: 1992), was not particularly low on any of the days, and in fact was only under 1 000 millibars on two occasions (20 October 1993 and 27 May 1994). It should also be noted that readings were taken at Christchurch Airport, some distance away, and do not necessarily correspond with the time of high tide. Freshwater flow in the Heathcote River is also unlikely to have had an impact on water levels either, with flows all being under 1 cumec.

Date	Height at Ferrymead (m)	Days since previous max. (days)	Air Pressure (mb)	Heathcote flow (cumecs)
20/10/93	1.408		996	0.783
17/11/93	1.521	28	1010	0.672
15/12/93	1.476	28	1007	0.795
10/01/93	1.440	26	1011	0.934
31/01/94	1.320	21	1017	0.723
02/03/94	1.520	30	1007	0.969
30/03/94	1.354	28	1020	0.666
29/04/94	1.276	30	1024	0.659
27/05/94	1.508	28	991	0.819
25/06/94	1.489	29	1000	0.975
26/07/94	1.421	31	1001	no data
10/08/94	1.238	15	1014	no data

Table 6.2 High Tides at Ferrymead Bridge: October 1993 - August 1994

It is possible then that the 20 October and 27 May had a barometric component of 0.14 metres and 0.19 metres, respectively. The high tide on 2 March 1994 (1.520 metres) however, can not be satisfactorily explained by either low barometric pressure or high river flow. When compared with the extreme tide levels for the period 1974-1989 shown in Table 6.3, it can be seen that the 1993-1994 high tide levels were not particularly high. The maximums recorded in October 1993, March 1994 and May 1994 were lower than the maximums recorded in all previous years except for 1979 and 1987.

Year	Max. tide recorded at Ferrymead Bridge (m)
1974	1.689
1975	1.838
1976	1.767
1977	1.716
1978	1.771
1979	1.021
1980	1.729
1981	1.737
1982	1.737
1983	1.527
1984	1.527
1985	1.657
1986	1.587
1987	1.418
1988	1.576
1989	1.578
1994	1.521

After Oliver and Kirk: 1992

Table 6.3 Extreme Tides at Ferrymead Bridge

6.6 Summary

This chapter has presented data relating to the processes relevant to the Avon-Heathcote Estuary mouth. There were few extreme events recorded during the study period, with the only one significant storm occurring during July 1994. This resulted in flows in the Avon-River of a similar magnitude to the August 1992 storm, although no data is available for the Heathcote River. This storm was also associated with large (3-4 metres) northeast swell offshore from Pegasus Bay. The maximum tides recorded at Ferrymead Bridge were also relatively low when compared with data for the period 1974-1989. In sum then, 1994 was not a high energy year in respect of the Avon-Heathcote estuary mouth and the implications of this will be discussed in the following chapter.

Chapter Seven: Dynamics of the Avon-Heathcote Estuary Mouth

7.1 Introduction

The preceding three chapters have presented data on the morpholgy of the Avon-Heathcote estuary mouth and the processes that prevailed throughout the study period. Chapter Four presented data from 10 profile sites that were surveyed monthly between November 1993 and August 1994. Almost all of the sites surveyed underwent considerable change during the study period, experiencing both rapid erosion and accretion.

Chapter Five presented data on the Avon-Heathcote ebb tidal delta, based on time exposure photographs. Due to problems with the method, only limited information regarding the ebb tidal delta was obtained, although it was possible to construct a series of maps detailing the position of the delta terminal lobe. These showed that the throughout the study period the delta terminal lobe migrated onshore and become progressively less crescentic.

Chapter Six presented data regarding freshwater flows from the Avon and Heathcote rivers, offshore wind and waves, and tides incident at Ferrymead Bridge. Only one high energy event was recorded during 1994, an easterly storm that hit Canterbury between 25-27 July. During these three days, 82 millimetres of rainfall was recorded at Christchurch Airport, causing high flows in the Avon River and large northeast swell (3-4 metres) were forecast for Pegasus Bay. Apart from this, none of the process variables exhibited high energy or extreme characteristics.

This chapter will integrate the data presented in the three preceding chapters to construct a picture of the dynamics of the Avon-Heathcote estuary mouth.

7.2 Factors Influencing Estuary Mouth Morphology

This study has demonstrated that there was only one significant storm event between November 1993 and August 1994 but despite this there was severe and sustained erosion recorded at a number of the profile sites. It is however noteworthy that the magnitude of beach change declined markedly with distance from the estuary mouth to the north, with very few changes occurring at Profile One. This suggests that the processes responsible for beach change were peculiar to the mouth of the Avon-Heathcote estuary. The patterns of erosion and accretion therefore arose from the unique interaction between the wave climate, tidal flows and ebb tidal delta present in the vicinity of the study site and substantial changes occurred in the absence of any high energy storm events.

In order to analyse the dynamics of the estuary mouth it is necessary to break the estuary mouth into components which can be viewed separately. At least five broad, yet distinct components can be identified;

1) The ebb tidal delta system.
2) The beach area on the eastern side of the South Brighton spit.
3) The beach area in Clifton Bay.
4) The beach areas directly adjacent to the inlet gorge.
5) The sand deposits just inside the estuary.

These distinctions are made on the basis of their relative exposure to two process variables; tidal currents and wave action. The assumptions being that ebb tidal delta morphology was primarily a reflection of the balance between tidal currents and wave action (Hubbard, Oertel and Nummedal, 1979, Oertel; 1988), the morphology of the seaward facing sand beaches were primarily controlled by wave action and the morphology of the inlet gorge margins and the sand deposits inside the estuary were primarily controlled by tidal currents.

7.2.1 The Ebb Tidal Delta

In Chapter Five it was shown that the seaward margin of the Avon-Heathcote ebb tidal delta fluctuated in both onshore/offshore and longshore directions. In addition to this, the delta margin became increasingly flatter throughout the study period.

If the mouth was tidally dominated then it would be expected that the delta would have a strongly crescentic shape (Figure 2.3d), reflecting the influence of the ebb tidal jet moving sediment offshore, with the crescentic shape being a result of the maximum tidal currents being restricted to a narrow channel. Conversely if the estuary mouth was wave dominated then the delta would be flatter, reflecting the dissipation of wave energy more or less equally along the length of the delta terminal lobe (Figures 2.3a-c). Using the delta shape as a means to infer the relative dominance between wave and tidal energy strongly suggests that the estuary mouth was wave dominated throughout the study period. This is also supported by the swell data presented in Chapter Six that shows an overall increase in swell height throughout the study period.

The onshore/offshore location of an ebb tidal delta is a result of the interaction between tidal currents, moving sediment offshore and wave induced currents, moving sediment onshore (Dean and Walton, 1975; Finlay, 1978; Hubbard, Oertal and Nummedal, 1979). In the case of the Avon-Heathcote ebb tidal delta it would be expected that during sustained periods of small northeast swell and small to moderate southerly swell, where substantial energy is lost during refraction in Pegasus Bay, that the delta would migrate offshore. Conversely, it would also be expected that during periods of sustained moderate to large northeast swell or large southerly swell that the delta would migrate onshore.

With this in mind, an attempt was made to correlate swell height and direction with the onshore/offshore location of the ebb tidal delta. The first regression plotted mean swell height for the periods between each photograph against the distance of the delta margin offshore from Shag Rock. This yielded a positive correlation of $r^2 = 0.23$, which is not statistically significant at the 0.95 confidence level. Swell height for the preceding five days before the photograph was taken was also plotted against the onshore/offshore location of the ebb delta margin. This yielded a slightly higher positive correlation ($r^2 = 0.35$) although this was not a statistically significant result either. Plotting the percentage of southerly swell between each photograph against onshore/offshore direction gave a positive correlation of $r^2 = 0.04$, also a statistically insignificant result.

In addition to this it was expected that wave direction and energy would also be contributing factors to the longshore location of the ebb delta margin. Throughout the study period the most seaward point of the ebb delta margin moved both north and south, as shown in Table 5.3. The longshore location for each delta position was regressed against predicted swell direction for the preceding period. This yielded a correlation of $r^2 = 0.03$. It is also possible that the some of the changes in the delta longshore position were caused by slight variations in the orientation of the main ebb jet during the period between photographs (Hicks and Hume; 1993). However, an assessment can not be made of this possibility due to the lack of quantitative data derived from the time exposure photographs.

These regressions therefore demonstrate that there was little, if any, relationship between swell height and direction and the delta margin position. There could be three possible reasons for this:

1) The offshore swell predictions were not representative of wave conditions at the delta.

2) The delta may have been responding to events occurring over a longer time scale that this study did not pick up.

3) The assumption that the delta margin will move inshore under higher wave conditions is only partially correct with other factors, such as longshore current direction and velocity, also being important.

Burgess (1968) demonstrated that deepwater southeast swells would arrive in southern Pegasus Bay as an easterly wave train and that considerable energy is lost due to refraction. The accuracy of the swell predictions and the exact relationship between offshore swell height and corresponding breaker height at the delta are not known. So therefore it is not possible to assess the assertion that the low correlations were due to offshore swell characteristics not being representative of wave conditions at the delta.

It is also possible that throughout the study period the delta was responding to process conditions operating at a longer time scale. For example it is not known the extent to which the 1994 swell predictions differ from those in other years because the longer term record from Reid and Collen, (1983) only presents mean conditions relating to 27 years of data and, as discussed in Chapter Three, it was demonstrated by Trenberth (1977) that the incidence of southerly and westerly airflow may vary considerably from year to year, with evidence of a 10-15 year cycle. This means that changes in the delta during this study may have been responding to processes acting over a longer time scale.

Finally, the assertion that delta location is determined by the interaction between wave and tidal currents may be an oversimplification of the situation. For example wave refraction around ebb tidal deltas gives rise to distinct longshore currents and these may include a local reversal in current direction (Robinson, 1960; Smith and FitzGerald: 1994). In addition to this the availability of sediment may also be important.

In summary then, the increasing flatness of the Avon-Heathcote delta throughout the study period strongly suggests that changes in the delta were the result of wave characteristics incident at the mouth of the estuary. Correlations however, between swell height and direction and delta onshore/offshore and longshore position yielded no significant correlations. Therefore, despite significant changes in delta location being recorded between each photograph, it is not known what caused these changes.

7.2.2 South Brighton Spit

This part of the analysis focuses on the seaward facing beach on South Brighton spit covered by Profiles One-Four, discussed in Chapter Four. Despite large fluctuations in the volume of sediment and profile shape at most of these sites, two broad trends can be distinguished.

The first was the severe erosion centred around Profile Four. This was first detected in December 1993, with a channel being cut into the foreshore at Profile Three and later, during March 1994, the scarp being eroded. Erosion of the foredune at Profile Four began in January 1994, and by early March the dune had been completely removed. A channel was also cut across this profile line and the volume of sediment removed was such that a number of drums, which were part of a groyne system installed in 1948, were exposed. Profile One and Profile Two, while showing small fluctuations did not exhibit erosion any where near the scale of that at Profile Three and Profile Four at any time during the study period.

Superimposed on this severe erosion was a trend of strong accretion due to the onshore, and generally southwest moving, migration of a large slug of sediment. This was first detected at Profile Three in December 1993, and steadily moved onshore and eventually, by April 1994, had completely welded itself to the foreshore. It was also detected during the first survey of Profile Two in January 1994, and was in the later stages of welding onto the foreshore and by the next survey in early February, this was completed. Further south, the slug was not detected until February 1994 but then it continued to migrate onshore, completely welding itself to the foreshore by the end of May. The slug was not detected at Profile One, the most northern profile, at any time during the study period.

It can be seen then that there were two distinct things happening at these sites. Severe erosion of Profile Three and Four from January to April 1994 and substantial accretion at Profiles Two, Three and Four, associated with the onshore movement of sediment, between December and May. Profile One experienced neither the severe erosion nor substantial accretion recorded at the other sites, while

Profile Two recorded the accretion due to the onshore movement of the slug but not the erosion recorded and Profile Three and Four.

In each instance the onshore movement of the slug of sediment was recorded prior to the periods of erosion, which indicates that the sediment accreting the profiles was not merely a return of the same sediment that had earlier being eroded. It can be concluded therefore, that the erosion and accretion, although occurring almost simultaneously, were the result of two distinct set of processes. Because the magnitude of these events decreased with distance from the main inlet channel, with virtually no change being recorded at Profile One, it can also be concluded that these processes specifically related to the mouth of the Avon-Heathcote estuary.

Beginning with the onshore and southwest movement of the slug of sediment, the source of this is likely to have been sediment removed from the beach and stored in the offshore bar system, at some time prior to the start of this study. The onshore and southward movement of this sediment was facilitated the prevalence of 1-2 metre northeast swell that was prevalent during January 1994 (Figure 6.5). Between February and May however, when the slug was still moving onshore, the prevailing swell directions were south and southwest.

The southwest swell would have been travelling in the wrong direction to be refracted into Pegasus Bay so would have not been incident at the estuary mouth. Burgess (1968) demonstrated that southeast swell is refracted into southern Pegasus Bay so that it arrives almost parallel to the shore. It has been noted however that the way waves are refracted around ebb deltas can alter longshore currents, often causing localised reversals in direction (Robinson, 1960; Smith and FitzGerald, 1994). In the case of the Avon-Heathcote ebb delta, this means that often longshore currents close to the shore will be to the southwest, north of the delta and to the northeast, south of the delta, regardless of the offshore swell direction. This is shown in Figure 7.1 and can account for the continued southwest movement of sediment despite the relatively low occurrence of northeast east swell between February and May 1994.

The severe erosion recorded at these sites is a little more complicated. As previously mentioned, it occurred in the absence of any high energy events, with respect to wave climate, tidal range and freshwater discharge from the Avon and Heathcote Rivers. It in addition to this the localised nature of the erosion, centred around Profile Four, suggests that the erosion was the result of local processes rather than more general meteorological effects.

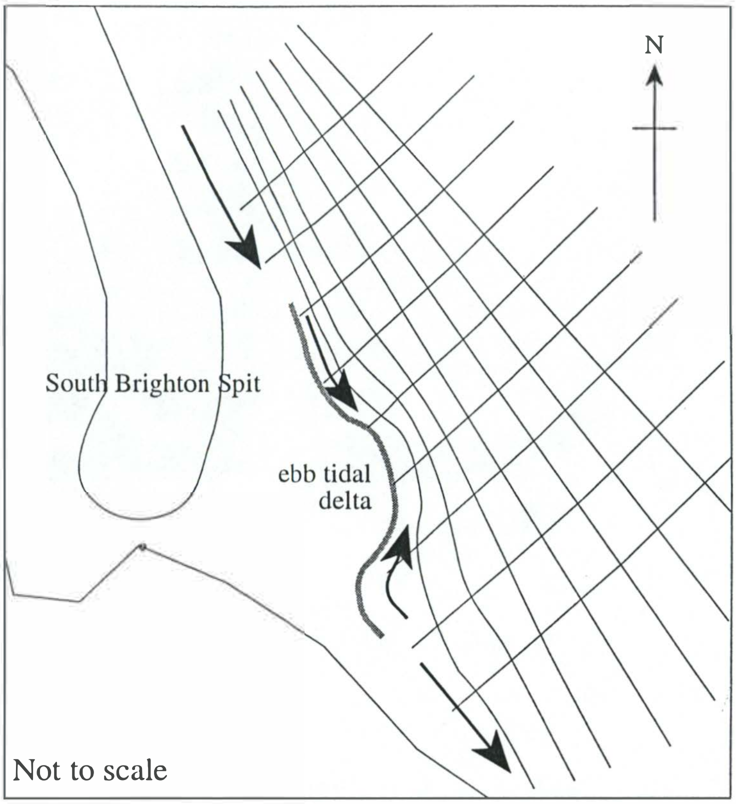


Figure 7.1a Sketch map of northeast wave refraction around the ebb tidal delta. Arrows indicate lonshore transport directions

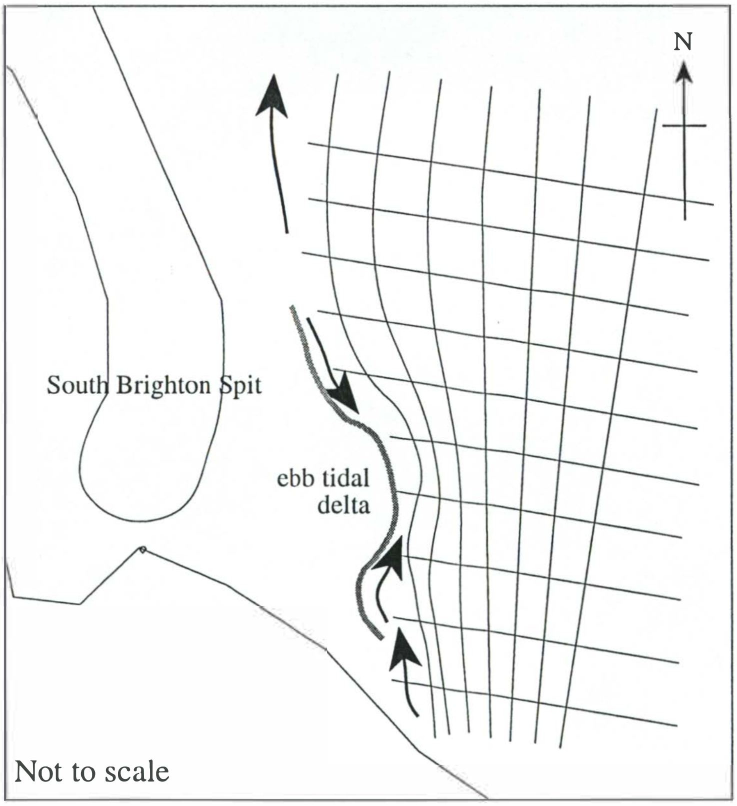


Figure 7.1b Sketch map of southeast wave refraction around the ebb tidal delta. Arrows indicate lonshore transport directions

As demonstrated in Chapter Five and discussed above in Section 7.2.1, between January and April 1994 ebb tidal margin migrated onshore, with the respective distances east of Shag Rock being 1 025 and 890 metres. It is unfortunate that there is no data for the delta during March and the photograph taken on 20 February is of a poor quality, because it makes it difficult to analyse the influence of the movements in the ebb delta system, during the period of severe erosion at Profile Four. It is likely however that the northern marginal flood channel migrated onshore in response to the onshore migration of the delta margin. Because one of the primary controls on wave breaking in shallow water is water depth (Galvin; 1972), the implication of the channel being closer inshore is that waves could travel further inshore before breaking. Therefore more energy could be expended on the foreshore.

In addition to this, it was shown that during March small channels formed on Profiles Three (Figure 4.7) and Four (Figure 4.8), within 100 metres of the scarp and foredune, respectively. This means that waves could travel very close inshore when the water level was higher at mid and high tide. The waves therefore did not break until they were relatively high up the foreshore, causing erosion on the part of the beach that would have only been subject to wave action during relatively high storm waves.

The wave climate itself during this period was characterised by offshore 1-3 metre swells from the south and southwest. As mentioned previously, however the southwest swell would not have been incident at the estuary mouth and the southerly swell would have been greatly reduced due to refraction into Pegasus Bay. Also during this period however, the prevailing wind was 10-20 knots from the northeast (Figure 6.4) and this would have introduced a significant locally generated wave component. Although these would have been small, they would have been steep, with short periods and therefore capable of causing considerable erosion (Burgess, 1968; Brown, 1976).

At Profile Four, while erosion was recorded during February, March and April, it was observed that the bulk of the erosion occurred in a two week period between the end of February and beginning of March. This coincides with the apogean tides shown in Figure 6.6, and although these were not particularly high when compared with extreme water levels recorded at the Ferrymead Bridge between 1974-1989, the maximum during this period was 1.52 metres on March 2. That was the second highest water level recorded during this study. The peak erosion therefore occurred at a time when water levels were at their highest, and the severe erosion of the upper foreshore and backshore was in part a reflection of these elevated water levels allowing wave action higher on the beachface.

An additional factor that can be considered, although not quantified, is an aspect of the model of ebb delta behaviour put forward by Smith and FitzGerald (1994) discussed in Chapter Two. During Stage II of their model of the Essex River ebb tidal delta, the swash bars that form near the delta terminal lobe migrate onshore. This causes the marginal flood channels to become constricted and therefore wave and flood current velocities are increased.

As stated above, between January and April 1994, the Avon-Heathcote ebb delta margin moved onshore and it would therefore be expected that this would have caused constriction of the marginal flood channel as suggested by Smith and FitzGerald (1994), with greater flood tide velocities eroding sediment from the lower foreshore. This is supported by the formation of the channels recorded at Profiles Three and Four and also erosion on the flood tide, as opposed to the ebb tide, is further supported in that a substantial amount of the eroded sediment was deposited inside the estuary, rather than offshore on the delta. This is also consistent with that by May severe erosion had ceased at these sites and this coincides with the delta moving back offshore (Table 5.3)

In summary then, the considerable accretion and erosion at these sites was the result of two distinct sets of processes. The accretion was largely from the onshore movement of a large slug of sediment and this, rather than being unique to this study period, is likely to be a continually occurring phenomenon due to the local reversal of longshore currents due to the refraction of waves around the ebb delta.

The erosion however was the result of several processes, including apogean tides, locally generated northeast waves and an onshore movement of the delta with associated marginal flood channel movement and subsequent increase in tidal current velocity. Because this is the first study that has recorded short term variations in the ebb delta position it is not possible to assess whether or not these movements were merely part of longer term fluctuations which regularly occur or if they represented an exceptional event in the behaviour of the ebb tidal delta. It is however known that the wave and tidal conditions were no where near those associated with extreme events. The erosion recorded at these profiles sites therefore was the result of the coincidence of all of these processes and while individually, none of the processes where particularly extreme, cumulatively they gave rise to erosion of a magnitude usually associated with an extreme event.

7.2.3 Clifton Bay

This section focuses on the beach in Clifton Bay, covered by Profiles Nine and Ten. The profile data for these two sites show that they behaved quietly differently from the sites on the other side of the main inlet channel as discussed in the previous section. Profile Ten showed consistent erosion throughout the study period although this erosion accelerated from the May survey onward. Profile Nine however, was less consistent than this and recorded periods of both erosion and accretion. In general, between December 1993 and April 1994, Profile Nine exhibited an eroding trend and then from April until August it displayed a generally accreting trend.

The consistent erosion at Profile Ten was intimately related to the behaviour of the ebb delta. Throughout the study period the marginal flood channel in the vicinity of this site migrated onshore. This meant that the strong flood currents were able to erode sediment from the foreshore. The accelerated erosion from the beginning of June onward was strongly linked to the increase in size of the shoal of sediment shown in Figure 5.8c. This shoal was fed by sediment flushed out of the estuary on the ebb tide and also by the sediment eroded from the beach in the vicinity of Profile Ten and, and although not visible until July, was probably increasing in size from at least March onward, when large increases in sediment were first recorded inside the estuary. The shoal then become considerably larger during August.

The growth of this shoal was both a cause of and a reflection of the erosion at Profile Ten. Firstly, refraction of waves around the delta, in a manner illustrated in Figure 7.1, meant that longshore currents in this area were probably predominantly in a northerly direction. The sediment eroded from Profile Ten therefore was transported toward the inlet channel and deposited on the shoal. In addition to this however, the growth of the shoal meant that the southern marginal flood channel was diverted around the shoal, with one branch running northeast and the other northwest, as shown in Figure 5.8c From Figure 5.8c it can be seen that by August this northwest branch was running very close to the shore and would have been getting steadily closer to the shore from April onward in response to the growth of the shoal.

Because this mechanism for erosion was self perpetuating it would be expected that erosion in the vicinity of Profile Ten would continue until the shoal enlarged to the extent that it reached Cave Rock to the south and become indistinguishable from the beach to the west. Subsequent onshore movement of the shoal would mean that the foreshore would temporarily increase in width. It would also mean that the flood flow would be deflected around the seaward margin of the shoal and these currents would steadily erode the new foreshore until a new equilibrium position was reached. This is a similar scenario envisaged by Smith and FitzGerald (1994) during Stage II and Stage III of their model, discussed in Chapter Two.

In addition to the erosion at Profile Ten caused by tidal currents, the deep water in vicinity of this site also meant that large southerly swell (up to 4 metres offshore) and moderate easterly swell prevalent during June and July were able to reach the foreshore, whereas immediately to the north this energy was dissipated over the shoal thereby reducing wave energy incident at the beach.

The erosion recorded at Profile Nine up until April did not seem to be related to the flood channel changes which affected Profile Ten but rather were attributed to high frequency of locally generated northeast waves between January and April. Because this profile ran directly into the steep sided, main inlet channel where the transition between the foreshore and relatively deep water occurs within a horizontal distance of only a few metres, waves could travel right up the foreshore before breaking, irrespective of their size. The presence of the main inlet channel, immediately to the north, did not impede the incidence of northeast waves at this site, and small waves (less than 0.3 metres) from this direction were frequently observed at this site. The steepness of these waves and the fact that almost all of their energy on the foreshore meant they were able to cause significant erosion, despite there small size.

The accretion of this profile from April onwards was result of the northward longshore transport of sediment eroded from the south, around the vicinity of Profile Ten. Deposition at Profile Nine also represented the northernmost extent that this sediment could be transported due to the presence of the inlet channel. In addition to this, the accretion at this site was also a reflection of the sediment being flushed out of the estuary on the ebb tide with accretion in April coinciding with the severe erosion of the beach South Brighton. The comparatively short lag time between erosion at South Brighton and accretion at Shag Rock shows that sediment is transported around estuary mouth relatively efficiently. This is a characteristic of 'tidally bypassing' estuaries discussed by Bruun (1978) and this efficiency suggests that the tidal prism of the Avon-Heathcote estuary has good flushing abilities.

7.2.4 Main Inlet Channel Beaches

This section discusses the two profiles that ran perpendicular to the narrowest section of the main inlet channel. Profile Five ran south into the channel from the spit and Profile Eight ran north into the channel from Clifton Bay. Both these profiles ran across narrow sections of beach before rapidly steepening at around the 0.5 metre contour, representing the margin of the main inlet channel. At both sites the channel margin was shown to fluctuate back and forth although the northern channel margin fluctuated within a greater envelope (50 metres) than the southern margin (20 metres). This reflected the presence of Shag Rock and the revetment in the vicinity of Profile Eight which enclosed the beach making the site similar to a small bay and thereby restricting the extent to which sediment could be eroded or deposited by tidal currents.

At the outset of the study, it was assumed that both these sites would be largely protected from wave action due to their orientation and any changes would be due to variations in tidal current velocity resulting from the change in tidal prism associated with the cycle between apogean and perigean tides. It was thought that any waves approaching Profile Five would have dissipated their energy over the broad foreshore on the seaward facing (southeast) part of the spit (Fig 4.21), with few if any working directly on the tip itself. Likewise, Profile Five was thought to be largely protected from wave attack by Shag Rock acting as a large 'breakwater'. Both these assumptions however were proved erroneous.

In the case of Profile Five, comparatively little change was recorded until March 1994. Although between March and May this site experienced considerable erosion. This erosion was linked to the events during March and April at Profile Four where the foreshore was severely eroded with the profile becoming considerably steeper and a small bay of relatively deep water formed. This meant that waves therefore travel inshore as far as the spit tip without breaking. They were then observed to be intensely refracted so that they were almost shore normal when the broke on the southern facing spit tip. During April and May waves around 0.5 metres high were observed to be incident at Profile Five, although from June onward no waves in excess of 0.2-0.3 metres were observed. This site accreted from May onward and this coincided with the deposition at Profile Four. With this was an associated increase in foreshore width at Profile Four, providing an wide area for wave energy to be dissipated over and thereby decreasing the energy received at Profile Five.

The foreshore at Profile Eight although protected from direct wave attack by Shag Rock, also experienced periods of erosion and accretion, and showed relatively substantial erosion following the easterly storm in late July. The large northeast waves associated with this storm were able to reach Shag Rock without breaking due to the deep water afforded by the main ebb channel. When they encountered Shag Rock however they were sharply refracted, giving rise to strong currents eddying clockwise around Shag Rock and eroding the beach behind. This turbulence was accentuated at high tide with the waves being reflected back off the rock revetment and sediment was scoured off the foreshore and into the main inlet channel. While the July storm was the only time that this was observed, it is assumed that the other periods of erosion between January and February and May and June, were the result of a similar scenario, with considerable erosion happening in the space of only 1-2 days.

In summary then, the lower foreshore and channel margins, at Profile Five and Eight, where shown to have fluctuated back and forth in response to minor variations in the main ebb channel. The upper foreshore at both sites however accreted and eroded in relation to the wave energy incident at them. However neither of the two sites were directly exposed to wave attack. In the case of Profile Five erosion was related to the condition of the beach in the vicinity of Profile Four and in the case of Profile Eight, erosion was the result of the strong currents and turbulent nature of the waves in response to striking hard rock obstacles.

7.2.5 Sand Deposits Inside Estuary

The two profiles inside the estuary, Profile Six and Seven, showed significant accretion throughout the study period. This accretion can be directly related to the erosion of the seaward facing profiles on the other side of the spit. In section 7.2.2 it was argued that this erosion was largely due to the onshore migration and constriction of the marginal flood channel associated with the ebb tidal delta. It follows then that, because sediment was being eroded on the flood tide, it would be expected that this sediment would be transported along the spit and into the estuary. Because current velocities were greatest in the constricted marginal flood channels and inlet gorge, deposition occurred just inside the estuary where the flow was no longer constricted.

Significant erosion began around Profile Three in January and continued until May, with the severe erosion of the spit tip at Profile Five. It was demonstrated in Chapter Four that the area immediately inside the estuary showed strong accretion until May and then the volume of sediment began to decline, reflecting that the seaward profiles were no longer acting as a source of sediment.

The immediacy of the decline in volume from May onward demonstrates that the sediment was not being stored in the estuary for long periods of time. This also suggests that the actual volume of sediment being transported into the estuary between January and May was much higher than the monthly volume calculations reflect. It is likely that, while sediment was transported into the estuary on the flood tide, it was then subsequently transported back out of the estuary on the ebb tide. This is characteristic of a tidally bypassing regime which occurs where the tidal prism is high compared with littoral drift (Bruun and Gerritson, 1960; Bruun, 1978).

Under a tidal bypassing regime there is little direct transport of sediment between the updrift side of the inlet and the downdrift side, rather sediment is transported into the estuary on the flood tide, temporarily stored, and then transported out of the estuary and down the coast on the ebb tide. This is precisely what occurred during this study with sediment being flushed out of the estuary and being deposited on the shoal, immediately offshore in Clifton Bay. This first become visible at low tide during July, although it would be expected that this would have been steadily increasing in volume from January onward reflecting the deposition of sediment eroded from South Brighton.

The growth of this shoal also suggests that sediment was being stored here rather than being subsequently being transported further down the coast. This is the result of Cave Rock acting as a natural groyne at the southern end of Clifton Bay with sediment being able to get past it and be transported to Sumner Bay, further to the south.

7.3 Summary

This chapter has demonstrated that the patterns of erosion and accretion recorded around the Avon-Heathcote estuary mouth were closely related to each other. This chapter broke the estuary mouth into sections and related the changes in each section to the processes that were active in determining their morphology. It was also demonstrated that there were linkages between each of the sections so a change in one part of the morphological system was reflected by a response in the other parts. This was particularly true in the case of the delta, where the onshore migration of the marginal flood channels was the primary cause of erosion at both the spit tip and in Clifton Bay. This erosion was subsequently reflected by strong accretion inside the estuary and on the Clifton Bay shoal.

It should also be noted however, that overall during this study the net transport of sediment was only in one direction. That is from north to south, with sediment being stored and steadily accumulating in Pegasus Bay. This also seems to be characteristic of the situation that has applied since the 1940s, as shown in Figure 3.3, which shows that periods of erosion at South Brighton are generally characterised by accretion in Clifton Bay. The scale of change recorded in this study therefore, while being of a seemingly magnitude, appears to be consistent with the long term processes acting at the mouth of the Avon-Heathcote estuary.

Chapter Eight: Conclusions

This thesis has been concerned with the morphology of the mouth of the Avon-Heathcote estuary. It presented data from ten profile sites surveyed at monthly intervals between November 1993 and August 1994. It also presented data about the Avon-Heathcote ebb tidal delta derived from a comparatively new method in coastal geomorphology, time exposure photography. An attempt was then made to relate the morphological changes at the estuary mouth to the prevailing process conditions in order to build up a morphodynamic model of estuary mouth behaviour.

In Chapter Four it was shown that many of the profiles experienced severe erosion and subsequent large amounts of accretion. The scale of change however decreased markedly with distance from the main inlet channel to the north, indicating that the beach profile changes were related specifically to local processes rather more general meteorological processes incident on the coast in general. The severe erosion also occurred in the absence high energy events, and the only storm during the study period had little impact on most of the profiles. This is in sharp contrast to the general literature relating to beach cycles which predict the most dramatic changes will occur to the beach profile during high energy storm events.

In Chapter Five, the Avon-Heathcote ebb tidal delta was shown to considerably vary it offshore/onshore position and longshore position in relatively short periods of time. Precise data relating to the ebb delta however was limited due to poor results from the time exposure photographs. For the first half of the study the results were marred by technical failures and during the second half of the study the application of this method was restricted by environmental conditions.

An attempt was made to relate the ebb delta changes to the prevailing wave climate although no correlations between offshore swell height and direction were found to exist. This is in contrast to studies of tidal inlet morphology on the United States' east coast, where the wave climate has been found to be an important control on ebb delta location and morphology. These studies however were carried out in environments characterised by broad coastal plains and straight coastline. This study however related to an environment in which wave processes were modified by a large volcanic peninsula to the south of the study site offering some protection from high energy waves from the south. It can therefore be concluded that the wave climate did not exert control over delta morphology to the same extent that has been found to be the case on the United States east coast.

Beach change was found to be strongly related to delta morphology and erosion at most of the sites was linked to the onshore migration of the marginal flood channels. Stronger flood flows due to the constriction of the channels and their closer proximity to the shore meant that sediment was eroded from the beach face and transported into the estuary before being entrained on the ebb tide and deposited on a large shoal that developed in Clifton Bay. This appeared to be part of a longer term process where periods of erosion at South Brighton are reflecting by progradation of the foreshore in Clifton Bay.

It can be concluded then that major changes were linked to seemingly small alterations in the inlet channel system. These channels are strongly related to the nature of the tidal currents flowing through them, particularly the main ebb channel where cross sectional area and tidal prism covary with each other. It follows therefore that any changes in the cross sectional area of the main inlet gorge, due to sand mining or dredging or changes to tidal prism due to increased drainage into the estuary or sea level rise, is likely to have a dramatic effect on the morphology of the estuary mouth. Not only on the ebb delta but also on the beaches in the immediate vicinity of the main inlet channel.

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